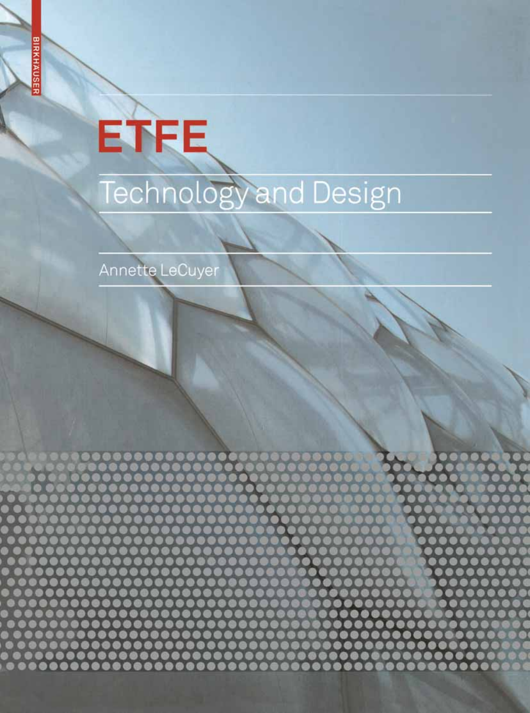

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ETFE

Technology and Design

Annette LeCuyer

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Annette LeCuyer

With contributions by
Ian Liddell, Stefan Lehnert and Ben Morris

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The enclosed sample is Fluon ETFE film of 250 microns thickness
which was used on the National Aquatics Center in Beijing.
We would like to thank AGC Chemicals for their kind donation
of these samples.

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Contents

Ian Liddell

Sustaining New Technologies

It is rare to have a new material introduced into the building construction industry that has had such an impact on the design and performance of buildings as ETFE foil. Over the past century there have been numerous examples of new materials and technologies that have been advanced by inventive engineers. In many cases, these materials have been popular for a brief period and then have died away to a lower level of use. Concrete shells were developed in the 1950s and flowered in the 1960s, but the change in building economics and design fashion and the exacting requirements of concrete technology finished them off. Fabric architecture blossomed in the 1980s and 1990s but since then has been in decline. Likewise, there was a marked change in the use of glass when float glass was introduced around 1955. With toughening and laminating techniques, larger panels were possible. However, the weight of glass and problems with fracture and seals have meant that multi layer construction on roofs is still risky and expensive. Now, ETFE foil cushions are providing new opportunities for lightweight, tough and durable enclosures, and there seems to be every reason for building applications of ETFE to continue to grow and diversify.

For me the story began back in 1980 when Buro Happold was working on a study to build a covered city in the Arctic, called 58 Degrees North. The site was in Northern Alberta about 160 kilometers north of Fort MacMurray on the Athabasca river where Syncrude was mining tar sands. The climate there is grim with very low temperatures in the winter and swarms of biting black fly in the summer. The study was led by a Canadian architect, Arni Fullerton, who had enlisted the help of a number of experts from Canada and Europe. These included Frei Otto, a research group from the architecture and building engineering department of Bath University led by Ted Happold, and Mike Barnes from City University in London. Other advisors included a cultural anthropologist, Ed Van Dyke; a horticulturalist, Peter Thoday, then at Bath University, who gave advice on conditions for plant growth; and a specialist on the impact on human performance of light and visual stimuli.

At that time, the engineering group was working on a research program on air-supported structures and the use of fabrics on buildings. There was a lot of pressure from the fabric industry to go for a PTFE/glass fabric solution.

1

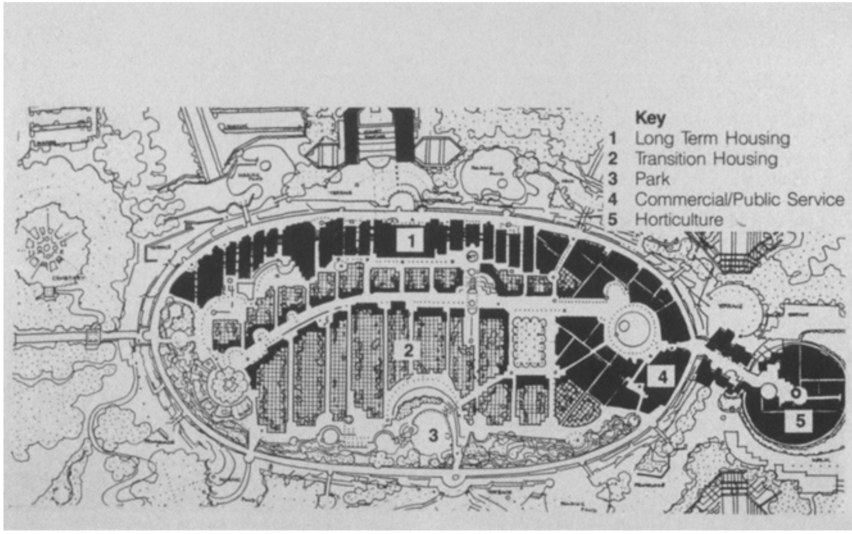
1__58 Degrees North, an enclosed City-in-the-Arctic scheme designed in 1980, was to be clad with ETFE cushions. /

After visiting some stadia with air-supported roofs, the team felt that this material – with about 10 percent translucency and dirty liners that gave a yellow tinged light – was the wrong answer. We believed strongly that the enclosing membrane for the arctic city had to be transparent to the full visible light spectrum to give stimulus to the occupants in the cold winter months and to enable plant growth. As well as being transparent, the cladding would have to be at least double skinned to provide some insulation and eliminate the build up of freezing condensation on the inner surface.

The obvious options were glass or rigid clear plastics, but both had major disadvantages. A representative from DuPont in Switzerland suggested using a fluoropolymer foil known as Tedlar. We had considered this material but had eliminated it because it was not flame resistant. Other alternatives on offer were Teflon-FEP and ETFE, which DuPont called Tefzel. FEP had already been tried at the Arnhem Zoo but had quickly torn. The DuPont representative explained that, because ETFE had a reasonable level of elastic behavior and remarkable toughness, it might be suitable. Tension tests were run at City University, and we discovered that ETFE had a very strange load extension curve with a small elastic range and a 400 percent strain to failure. This characteristic gave ETFE extraordinary toughness, making it practically impossible to tear since the crack tip – the sharp end of a crack where there are normally high stress concentrations causing the crack to propagate – always yielded.

The design team felt that ETFE must be the right answer for our proposed air-supported envelope enclosing 150,000 square meters. The structure was a cable net and the cladding was to be ETFE foil cushions 1.8 meters wide, the width of the foil sheet, with the edges fixed into a stainless steel profile with EPDM rubber gaskets. The proposal was received enthusiastically by the client Tom Chambers, who was the minister for Housing and Public Works in the state of Alberta. However, shortly afterwards the price of oil fell and the Syncrude expansion was abandoned. When it was restarted ten years later, robotic technology had reduced the need for large numbers of operatives, so the project was never built.

My next venture into the use of foil came when Buro Happold was asked in 1987 to advise on a scheme to



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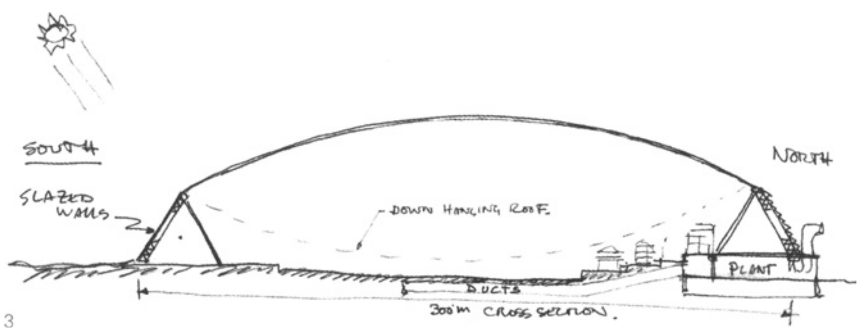

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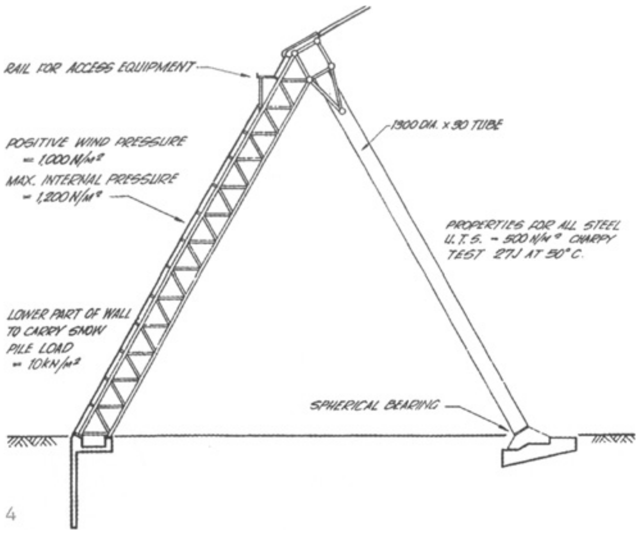
2__Plan for projected covered city with housing for 10,000 mining workers. /
3__Sketch cross section /

cover the atria, or internal streets, of the Chelsea and Westminster Hospital in London. The architects were thinking of a fabric roof but we proposed an aluminium structure clad with ETFE cushions, which would have better light transmission and insulation. The atria were planned to be semi-outdoor spaces with a system inducing an upward flow of fresh air ventilation. Some of the hospital rooms, with windows opening out into the atria, depended on these spaces for light and air. At this time, ETFE foil had been used for a few swimming pool enclosures. For these projects, the company Vector Foiltec had developed an aluminium framing system to hold three layer cushions of foil. Our roof structure, based on aluminium arches spanning 18 meters, incorporated drainage channels and concealed the inflation pipes for the ETFE cushions.

Since there was some nervousness about using a new material on an urban building, the ETFE scheme was compared with a conventional steel structure clad partly in steel sheeting and partly in glass. A detailed whole life cost analysis was carried out that demonstrated that ETFE foil offered significant advantages with low maintenance costs. The roof was built and so far has lived up to expectations. Importantly, this project also opened the door for ETFE cushions to be used on a range of urban buildings. The project architect for the Chelsea and Westminster Hospital atrium roof, who became deeply involved with the detailing of the aluminium, was Ben Morris, who then went on to join and develop Vector Foiltec.

The third project I want to mention is the Hampshire Tennis and Health Club, which was commissioned by a young company that wanted a new image for their club. The design team proposed to cover the tennis courts with a lightweight translucent ETFE foil roof that would make the courts feel like they were outside, but without the disadvantages of blinding sun, wind and rain. After discussions with Ben Morris, we opted for a roof with tensioned cables supporting ETFE cushions. A scheme was prepared and a price was agreed with the client that allowed for development work on the detailing. Unfortunately, the start was delayed by contractual negotiations and very little time was allowed for prototype evaluation. Notwithstanding the fast pace of the contract, and after some hiccups, the structure was completed in 1995 and the tennis halls have been a huge success ever since.



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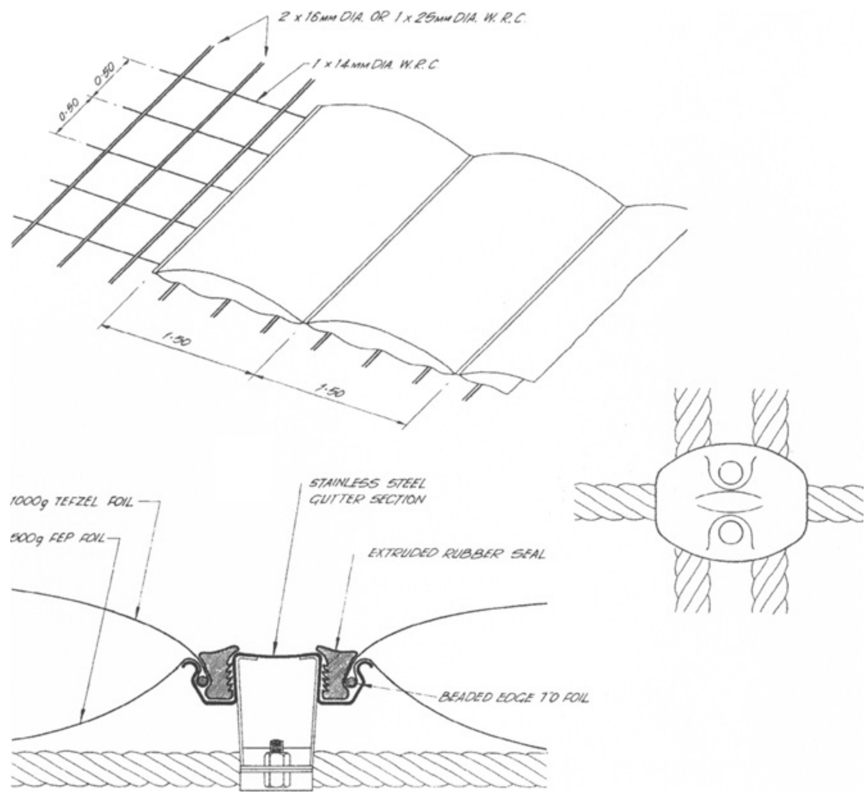

4–5__Details of external wall with ETFE cladding /

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The outer and inner foils are white tinted to about 50 percent translucency. The sun is reduced to a small red dot, eliminating all glare and making ideal conditions for tennis. The result is that in summer all the interior courts are fully booked, while the external courts, which are free of charge, are hardly used. The experience of these tennis halls enabled the ETFE cushion system to be used on other cable structures, exploiting the benefits of wide spans with minimal structure. I always regret that we did not use ETFE foil on the Millennium Dome, but the technology at that time was not sufficiently developed to use it on such a time critical project.

Since these early applications, ETFE foil cushions have lived up to expectations of being remarkably robust and durable. Cuts do not propagate, even under severe wind effects, and can be repaired with ETFE adhesive tape. While walking on the cushions is not recommended, the roof of the Hampshire Tennis and Health Club now features a set of large indented footprints up one of the cushions where a maintenance man with heavily treaded boots has walked.

The exciting thing is that we now have a material that can be used for constructing large environmental enclosures and that has the potential to be used to realize the dream of covered cities. But will the technology follow the pattern of other new technologies and fade away? At present, there is interest in ETFE cushion enclosure systems from all parts of the world, and the amount of foil being installed is increasing annually. The evidence is that this proliferation is being driven by cost advantages and environmental benefits. However, the risk of the technology waning is also ever-present, arising from the possibility of systemic failures requiring expensive remedial work. With other new technologies such as air-supported fabric roofs, the seeds for failures were sown by the desire of project managers to drive down costs through competition and so-called value engineering. While ETFE cushion technology looks deceptively simple, it requires careful engineering and detailing to avoid problems. Foil engineers and contractors should be selected with care. Vector Foiltec, the pioneers, have worked tirelessly to understand the nature and behavior of ETFE and to make the innovations that have enabled this technology to succeed.

Introduction

Pleasure, Power and Payload

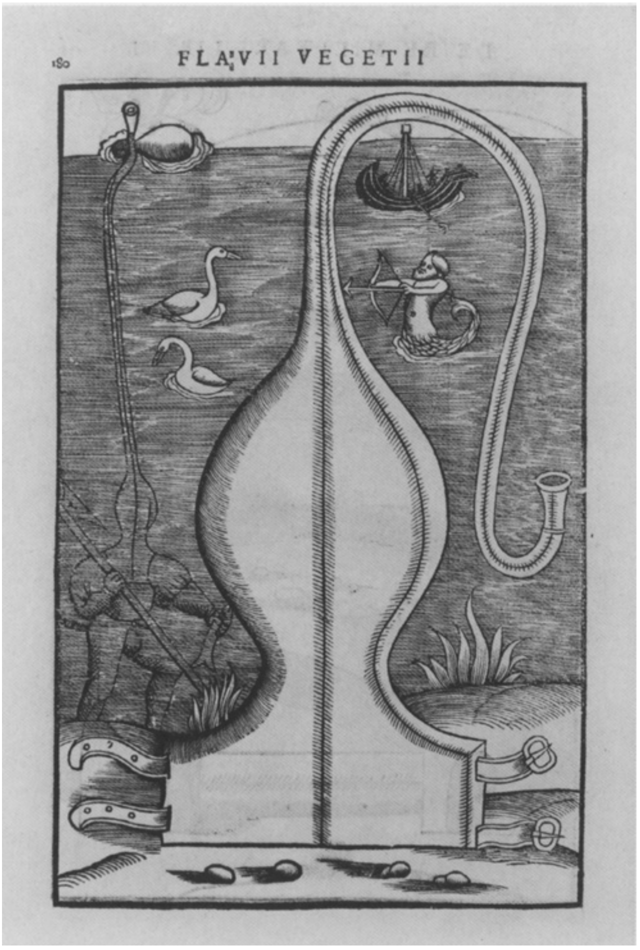
Pneumatics – ideas and technologies

Air, used as a building material, is a recent phenomenon in architecture. While the first half of the 20th century was dominated by innovative ideas, the second half witnessed the proliferation of increasingly ambitious built projects. As with many advances in architecture and engineering, this evolution is the result of a symbiotic relationship between the imagination and the application of new technologies. Because of their newness in architecture, pneumatics have tended to be identified with the avant-garde but, beyond the confines of the discipline, they have a long history.

Images from Assyria show warriors crossing rivers on air-filled goatskins,[1] and the Greeks and Romans used inflated animal skins both to make underwater breathing devices and air mattresses to rest soldiers.[2] In the 13th century, the idea of a lighter-than-air balloon was suggested by Roger Bacon, a Franciscan friar who mixed mysticism, alchemy and scientific methods of inquiry to imagine a "huge globe of thin metal that would rise to the heavens when it was filled with the very thin air of the upper atmosphere."[3]

In pursuit of pleasure, it is suggested that Leonardo da Vinci, who drew flying machines and, like many artists of the late 15th century, used pig's bladders for the practical purpose of storing pigments, was also perhaps "...the earliest artist to have understood the inherent aesthetic character of air, [when he] created a pneumatic environment by using inflated pigs' bladders in a small room."[4] By the latter half of the 17th century, Father Francesco Lana advanced the scientific imagination by proposing a spherical balloon of thin copper sheet that would work on the basis of a vacuum.[5]

In 1783, these lighter-than-air ideas became real when the Montgolfier brothers, French paper manufacturers and amateur scientists, sought "to enclose a cloud in a bag" and successfully launched a linen bag lined with paper that was 107 meters in diameter and filled with air heated by a fire.[6] Their experiment quickly transformed into a spectacle when they repeated the demonstration before the king at Versailles in the presence of an estimated 100,000 spectators, who flocked to the event "like pilgrims drawn to a hearsay miracle."[7] Made of cotton lined with paper, the Versailles balloon introduced the concept of



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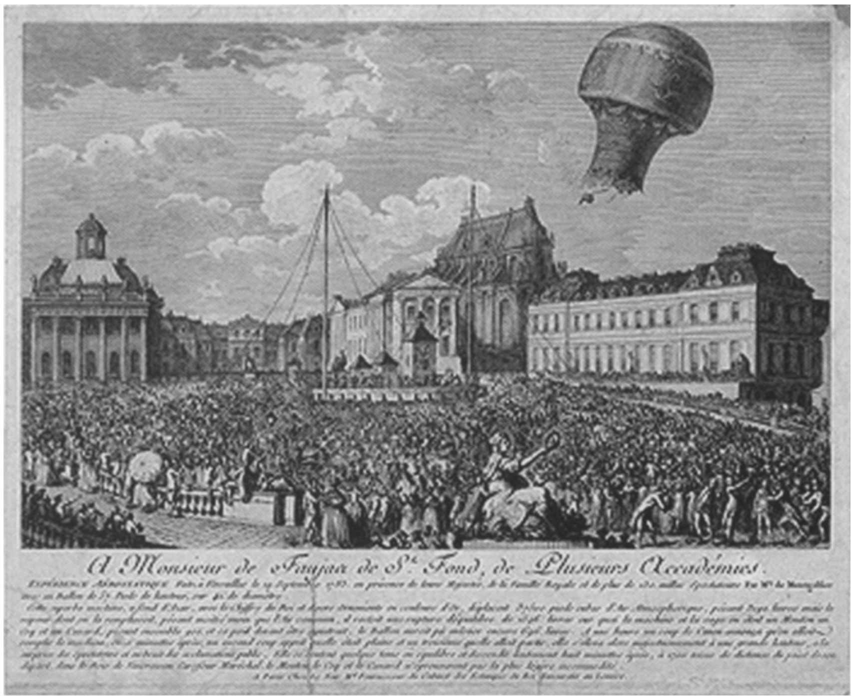
1–2__Engravings from *Scriptores rei militaris*, 1532, show Roman use of inflated animal skins for underwater breathing devices and air mattresses. /

payload by carrying a sheep, a duck and a rooster. Several months later, another Montgolfier balloon inaugurated manned flight and was followed closely by the journey of Jacques Charles and Nicholas Robert in a hydrogen-filled valved balloon made of rubber-impregnated silk.[8] By the end of 1783, balloon flight, previously only imaginable, "...was rapidly becoming a popular, romantic and ubiquitous adventure."[9]

Pleasure and power were inextricably intertwined in the balloon. Although the Montgolfier balloon was decorated with golden fleurs-de-lis to flatter the king, an observer of the event concluded that it turned the civil, moral and political world upside down; that religion had become subservient to science; and that man was master of nature. With the benefit of hindsight, the contemporary historian Simon Schama reinforces the profound implications of the balloon at Versailles: "Instead of being an object of privileged vision – the specialty of Versailles – the balloon was necessarily the visual property of everyone in the crowd. On the ground it was still, to some extent, an aristocratic spectacle; in the air, it became democratic...As a spectacle, it was unpredictable; its crowds were incoherent, spontaneous and viscerally aroused...The sense that they [the crowd] were witnessing a liberating event – an augury of a free-floating future – gave them a kind of temporary fellowship in the open air."[10]

Notwithstanding this democratic spectacle, as instruments of strategic power, balloons were readily appropriated for military applications, including aerial observation of battlefields and supervision of artillery fire, initially by Napoleon's troops and then in numerous conflicts up to and including World War I. In 1849, the notion of payload became more aggressive when the Austrians bombed Venice using 200 small hot air balloons, which had only limited effect because of unpredictable winds.[11] Balloons were also adopted as a means of transport for polar explorers, but they were unmanageable and easily fell prey to the whims of severe weather and atmospheric conditions.

By 1900, to overcome this problem, Montgolfier's "globe airostatique" had evolved into the cigar-shaped dirigible, or directable, airship with a steering structure. Seeking a lightweight propulsion system for these lighter-than-air ships, coal and steam were superseded by gasoline and the internal combustion engine. Dirigibles were appropriated



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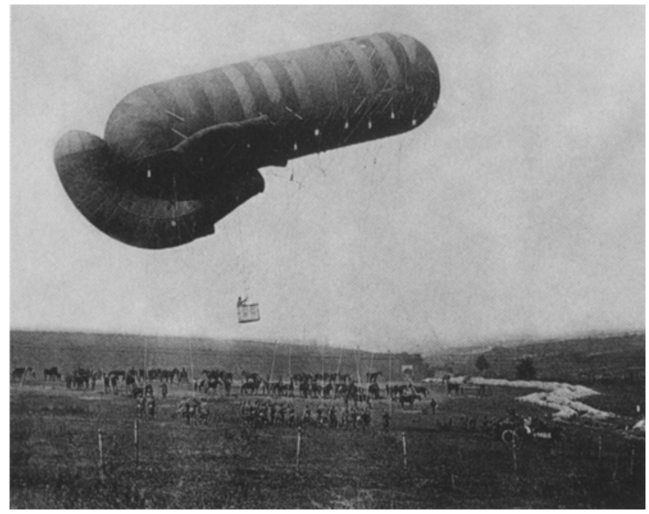

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3__Montgolfier's balloon at Versailles in 1783 honored the king, yet symbolized nascent democratic power. /
4__Kite balloons were used for aerial supervision of battlefields from the Napoleonic Wars through World War I. /

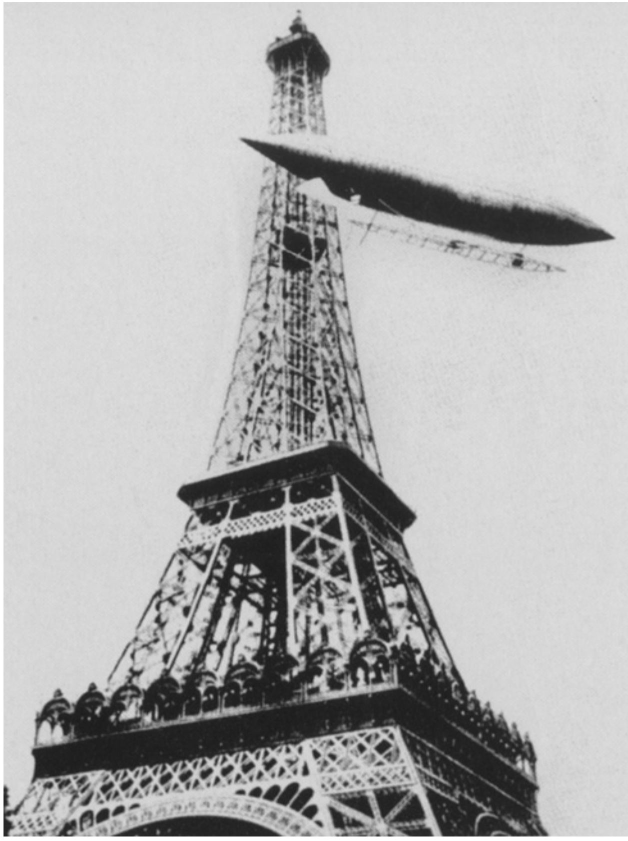
for military applications and, in the civilian domain, expanded the concept of payload, logging thousands of kilometers of transatlantic passenger travel. However, filled with hydrogen, they repeatedly fell victim to catastrophic fires, and the travel and tourism enterprise came to an abrupt halt with the fiery crash of the Hindenburg in 1937. Nonetheless, during World War II, balloons continued to be used for exploration and as defensive barrages; airships for minesweeping and reconnaissance work; and inflatables for decoys and temporary buildings.

In their publication *The Architecture of War*, Keith Mallory and Arvid Ottar observed, "During 1900–45, one can identify the emergence of two strands of military building activity: firstly an evolutionary strand which countered new developments like the tank simply with further variations on the theme of fortress design; and secondly a strand which responded to real quantum shifts in the availability of technology, in an altogether more innovative way."[12] This second strand focused on lightness, providing fertile territory for thinking beyond the airship to the development of air-supported structures for terrestrial defense, high altitude scientific research and the Space Race. The advances of these programs would in turn have a profound impact as they percolated from the powerful military-industrial complex into the public realm.

Paradise – ideas and technologies

In parallel with the evolution of theories and technologies of pneumatics is the history of attempts to both imagine and build an ideal environment. One of the oldest and most enduring ideas is the notion of a garden paradise. The Garden of Eden, documented in the Old Testament and with a name derived from the Hebrew word for "delight," is a concept manifest in many ancient cultures. The word "paradise" connotes garden, circular enclosure and wall. In both Eden and paradise, the earthly garden is bounded, with the perfected and pleasurable harmony of human beings and nature within the garden starkly contrasted with a hostile environment beyond. Paradise was also pursued pragmatically, notably by the Romans, who created artificial climates in heated enclosures.[13]

During the Renaissance, humanistic preoccupations produced another iteration of the ideal world. The imaginary island in Sir Thomas More's book *Utopia*, written in



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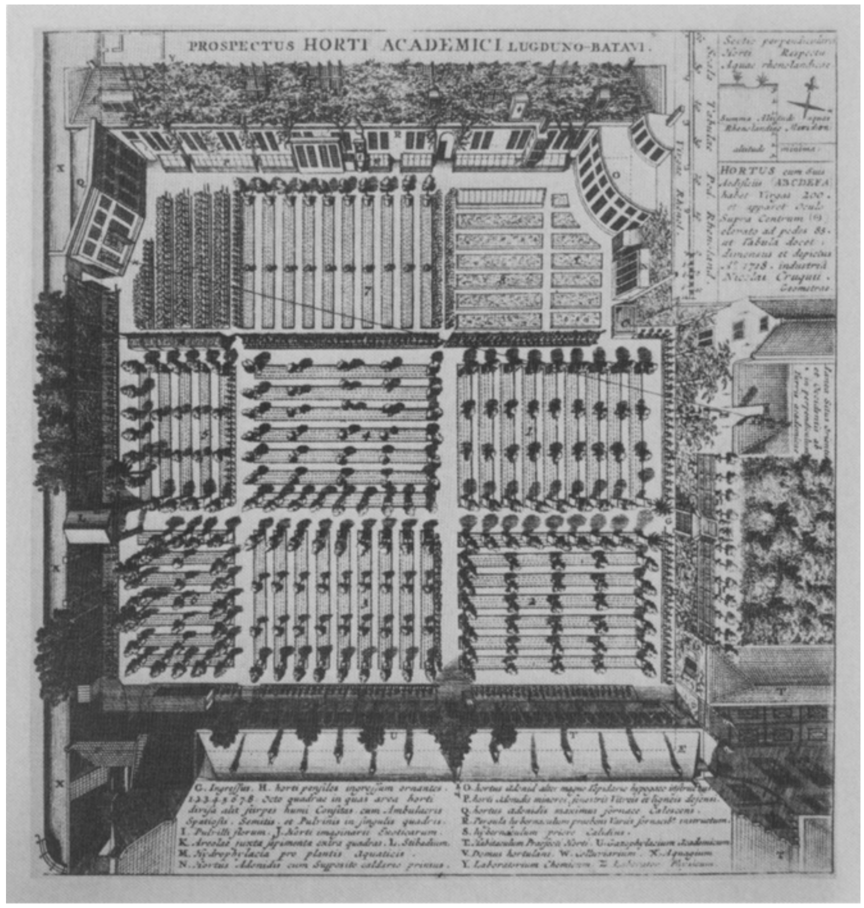
5__In 1901, an early dirigible won a prize for navigating an 11 km round trip from St. Cloud to the Eiffel Tower in 30 minutes. /
6__The Garden of Eden contrasts harmony of man and nature within the bounded domain with a hostile environment beyond. /

1516, was the conceptual site of a perfect social and political system. Focusing principally on man's relations to fellow man, the concept of Utopia was nonetheless, like the Garden of Eden, a bounded domain in which harmonious social relations were posited in opposition to harsh conditions elsewhere. At the same time, the systematic study of nature in the Renaissance produced botanical gardens, the first in Padua in 1543, which sought to gather the world into a single domain. These early scientific versions of the Garden of Eden advanced with the creation of artificial climates for growing plants deveoped in greenhouses.

By 1654, in a treatise on forcing and greenhouse gardening called *The Garden of Eden* published by Sir Hugh Platt, the sacred ideal had seemingly been subordinated to secular realities, although "[g]reenhouse gardening still had overtones of profane conjuring." [14] During the 17th and 18th centuries, following the same path as pneumatics, the secular transition was more emphatic. The British and Dutch financed seed and plant gathering expeditions around the world and, at home, developed increasingly sophisticated gardens and buildings to house them, creating what was effectively an "environmental machine." A private zoo and gardens near Leiden were described by the Swedish naturalist Carl Linnaeus as "masterpieces of Nature aided by Art." [15] The enclosed, perfected world imagined in the Garden of Eden was being energetically constructed by man.

By 1817, when John Claudius Loudon, an entrepreneur engaged in the burgeoning business of gardening, praised the ability of glasshouses to "...exhibit spring and summer in the midst of winter...to give man so proud a command over Nature," the harmonious balance of the Eden ideal had been profoundly shifted. "[This] culture of environmental fantasy," [16] coupled with the abolition in Britain of the glass tax in 1840 and the development of economic methods of mass producing glass, led to a dramatic increase in the construction both of conservatories – which created benign artificial environments for plants by using heat, ventilation and shading devices – and of glazed arcades and atria to provide similar advantages for human beings.

The technological advances that generated the great 19th century horticultural glasshouses culminated in the Crystal Palace, designed by the gardener Joseph Paxton,



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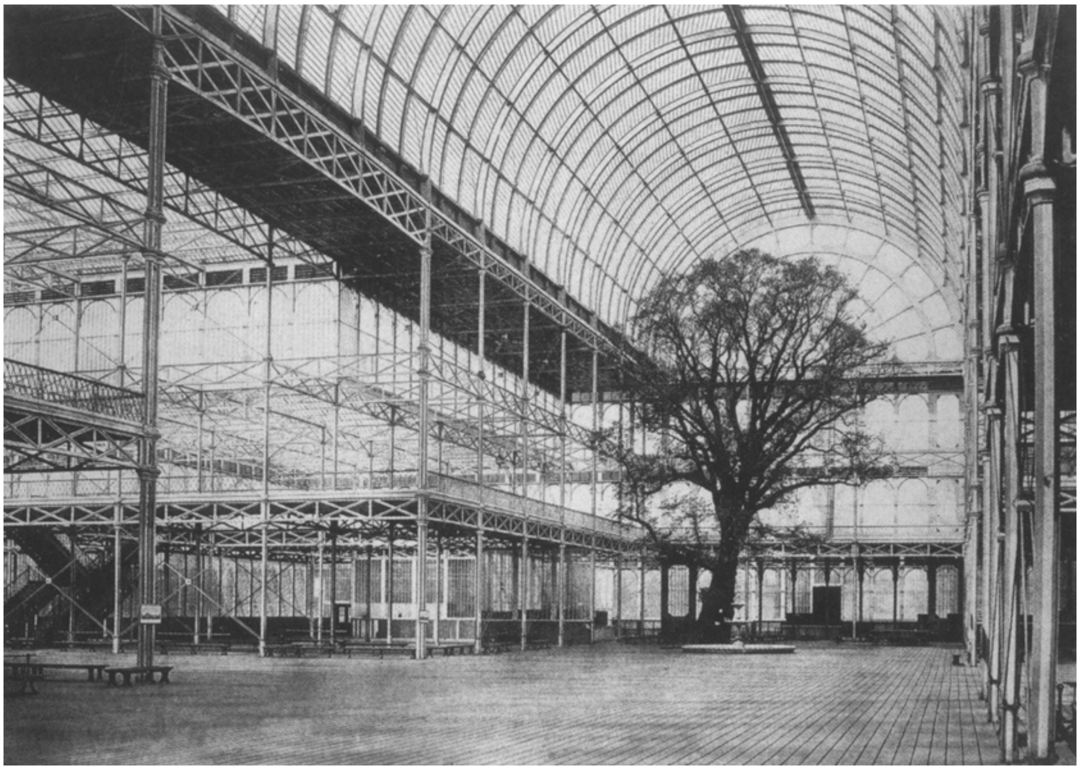
7__Leiden University Botanic Gardens, as recorded in 1718, were foremost among man's efforts to gather nature into a constructed and secular Garden of Eden. /

which translated man's command of nature into an overt statement of political and economic power. The perfect and harmonious Garden of Eden was the empire and its fruits the greatest global collection of man-made goods and chattels ever assembled. Nature was not entirely banished from this garden of commerce, with the building enveloping enormous mature trees on its site in Hyde Park. The profound impact of this immense environmental enclosure, the largest ever constructed at the time, was recorded by Richard Lucae, a 19th century German critic: "As in a crystal, there is no longer any true interior or exterior. The barrier erected between us and the landscape is almost ethereal. If we imagine that air can be poured like a liquid, then it has, here, achieved a solid form, after the removal of the mould into which it was poured. We find ourselves within a cut-out segment of atmosphere. It is, in my opinion, extraordinarily difficult to arrive at a clear perception of the effect of form and scale in the incorporeal space."[17]

Lucae's language, in addition to suggesting a paradisiacal experience in which the vault of the sky has been built by man, also foreshadows the terminology of pneumatic structures that would be developed during the 20th century. Likewise, the Crystal Palace – erected in just six months, enjoyed for the five months of the Great Exhibition, then swiftly dismantled – was, like Montgolfier's balloon, seemingly spontaneous and ephemeral. This new sense of lightness in buildings, both actual and phenomenal, was to contribute significantly to the emergence of pneumatic forms of architecture. During the 20th century, the pneumatic imagination[18] and visions of a perfect world would intersect to produce a new generation of theories and proposals for the built environment, each manifesting a different synthesis of the desires for pleasure, the imperatives of political and military power, and the economic necessities of payload.

1__ Adriaan Beukers and Ed van Hinte. *Lightness* (Rotterdam: 010 Publishers) 1998, p. 157.
2__ Leonard C. Bruno. *The Tradition of Technology* (Washington DC: The Library of Congress) 1995, p. 18.
3__ Roger N. Dent. *Principles of Pneumatic Architecture* (New York: Halstead Press Division, John Wiley + Sons, Inc.) 1972, p. 24. Refers to *History of Airships* by B. Clarke.
4__ W. Sharp. "Air Art," *Architectural Design* (March 1968) p. 99.
5__ Dent, op. cit., p. 24.
6__ Bruno, op.cit., p. 209.
7__ Simon Schama. *Citizens – A Chronicle of the French Revolution*



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8__The Crystal Palace of 1851 exemplified the architectural quest for lightness that would emerge to dominate the 20th century. /

(New York: Alfred A. Knopf) 1989, p. 124.
8__ Bruno, op. cit., p. 109.
9__ Id. at p. 209.
10_ Schama, op. cit., p. 131.
11_ Beukers and van Hinte, op. cit., p. 154.
12_ Keith Mallory and Arvid Ottar. *The Architecture of War* (New York: Pantheon Books) 1973, p. 269.
13_ John Hix. *The Glass House* (London: Phaidon Press Ltd) 1974, p. 9.
14_ Id. at p. 10.
15_ Id. at p. 13.
16_ Id. at p. 19.
17_ John McKean. *The Crystal Palace* (London: Phaidon Press Ltd.) 1994, p. 32.
18_ The phrase "pneumatic imagination" is from the essay by Marc Dessauce entitled "On Pneumatic Apparitions" in *The Inflatable Moment* (New York: Princeton Architectural Press and The Architectural League of New York) 1999, p. 13.

The Pneumatic Imagination

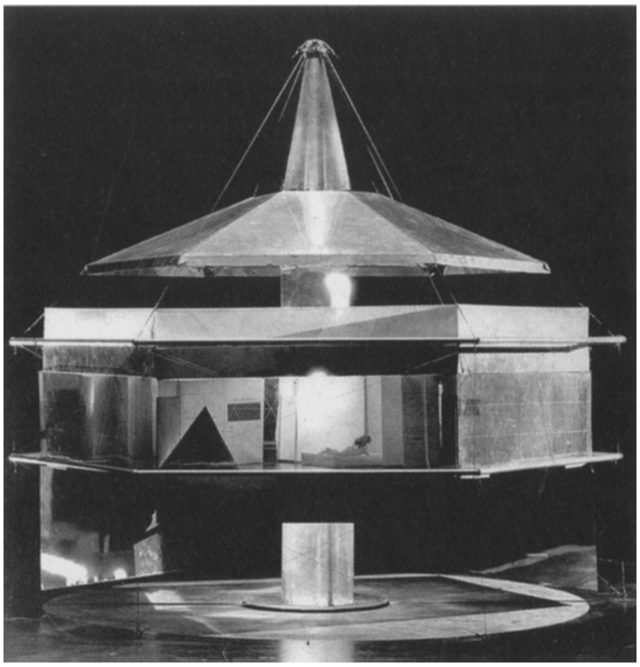
Architectural Ideas and Applications

The first pneumatic building proposal is attributed to Frederick William Lanchester, an English engineer, who patented a design for a field hospital in 1917. This fabric tent without poles or conventional structure was to be supported by low air pressure and entered by means of air locks. Some 20 years later, collaborating with his architect brother, he designed a pneumatic exhibition building 300 meters in diameter that was supported by air pressure and restrained by a cable net.[1] In 1942, prompted by the demands of the War Production Board in the United States, engineer Herbert H. Stevens and designer Al Bush developed a scheme for an airplane factory with a clear span structure of 366 meters that was to be achieved with 1.2 millimeter thick steel sheet supported by air pressure.[2] With technology lagging behind the imagination, all of these projects were unbuilt.

Lightness

Buckminster Fuller – whose wide-ranging visionary intellect engaged him in design, science and industry and as a consultant to business and government – made major contributions to both the concept of lightweight structures and their construction. Fuller drew attention to the issue of lightness in buildings by critical examination of their weight compared to more efficient ships, airships and airplanes. At various points in his career, he developed ideas and constructed prototypes for lightweight transportable structures for military use and, for a period after World War II, promoted ideas aimed at converting military technology to civilian applications.

Payload became a central preoccupation for Fuller. The concept of lightness, of doing more with less, was an index of both industrial efficiency and environmental responsibility. In 1951, long before sustainability assumed its environmental mantle, he coined the term “Spaceship Earth,”[3] which recognized the planet as a secular Eden, a bounded and benevolent domain in which survival depended on the harmonious balance of man and nature. This enduring theme in his work surfaced again in 1969 in the book *Utopia or Oblivion*, which contrasted the ideal with its potential failure. Throughout his life, Fuller sought to apply his sweeping ecological philosophy through design proposals. His early Lightful Houses research focused on new forms of mass housing that were both “lightweight”



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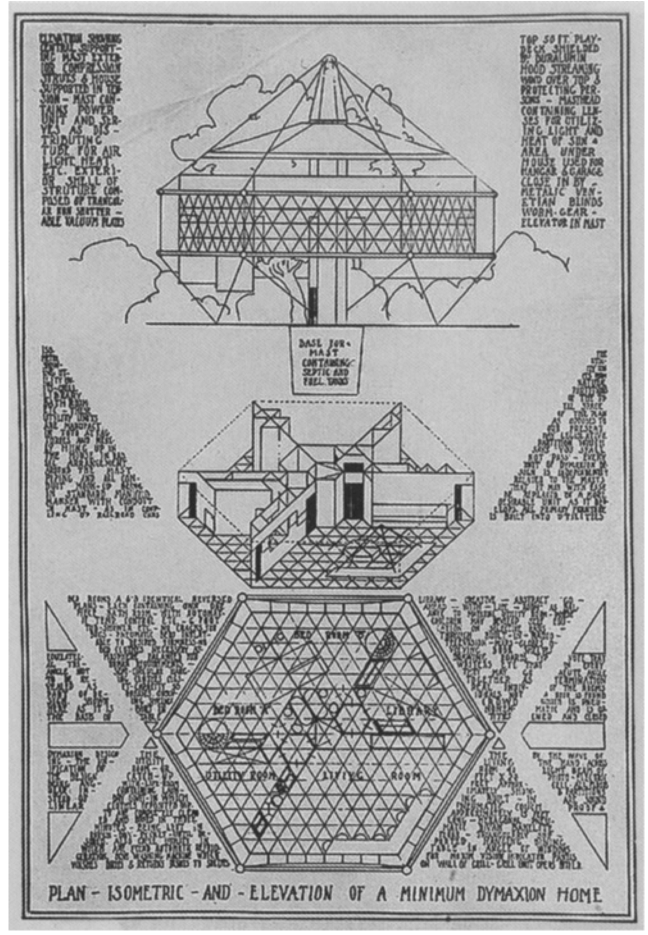

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1__Buckminster Fuller's 1929 Dymaxion House proposal incorporated pneumatically stressed structural components. / 2__Plan, isometric and elevation /

and, like paradise, "de-lightful." The houses, which featured tensile structures and were made of new lightweight materials that were prefabricated, were to be transported to site by helicopter and conceptually moored like airships, touching the earth lightly. These evolved into the 1929 Dymaxion House – the name a fusion of the terms dynamic and maximum – a mass-produced single family dwelling conceived as an analog of a natural system such as a tree or human being. The central mast of the house was to be "made of duralumin tubes, inflated to high pressure, in triangulation with piano-wire steel – similar to a battleship mast or a dirigible mooring...The floors likewise, in tension between their triangular supports, are softened by pneumatic pressure between two flexible shells, the upper one which might be something like synthetic approximations of leather."[4] The Dymaxion House was not realized and, by the time that the concept evolved into the prototypes of the Wichita House, which were constructed in 1944–46, pneumatics no longer played a structural role.

Fuller's development of lightweight geodesic and tensegrity structures is credited with helping scientists and doctors to recognize these same structures in nature.[5] The dual significance of geodesics has been described in the following terms, which allude to both payload and paradise: "As technical artifacts, they aimed at maximum efficiency in the relationships of volume to weight, use of materials to useful surface, and assembly time to mobility. As sociocultural alternatives to typical rectangular architecture, the dome crystallized society's dreams of a life liberated from constraints and tutelage."[6] Pneumatics and geodesic principles came together in a collaboration between Fuller and Berger Brothers of New Haven, which produced lightweight domes using pneumatic sandwich panels made from a dual-walled membrane held together by drop threads.[7] This fabric was manufactured in a single weaving process, which had been developed concurrently by Goodyear in the US using the trade name "Airmat," and by the military Research and Development Establishment at Cardington in the UK.[8]

Bubbles and paradise

Fuller also produced the Garden of Eden projects, a series of geodesic studies that included a house built in the Hollywood Hills in 1962 and the steel framed, acrylic clad

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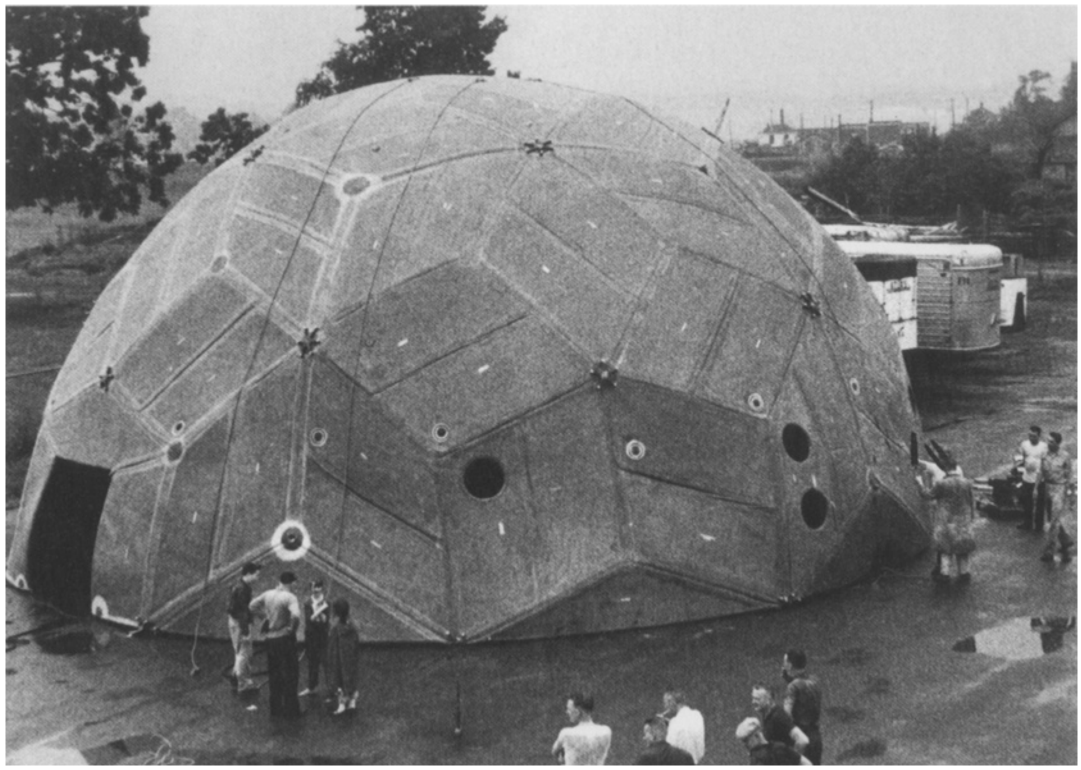

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3__The US Pavilion for the 1967 Montreal Expo, designed by Buckminster Fuller, was a 76 m diameter two layer geodesic dome clad with transparent acrylic panels. /
4__Buckminster Fuller's prototype for a pneumatic geodesic dome was made from a dual-walled, single woven membrane. /

US Pavilion for the 1967 Montreal Expo. In these buildings, in which the bounded domain of paradise was manifested as a constructed vault of the sky, "...Fuller pursued the goal of optimum development of geodesic domes as 'environmental controls,' as spatial and climatic skins, as regulators and valves of the desired exchange with the environment...The idea was to work together with Nature."[9] Although not air-supported, these structures were conceived as approximations of pneumatic membranes[10] and were presented by Fuller and discussed in the popular press as bubbles. Both pneumatic and ephemeral, bubbles proved to be compelling imagery for Fuller's crusade for lightness, making tangible a concep-tual connection he had expressed as early as 1938 in *Nine Chains to the Moon*, in which he recorded the formula:

Efficiency = doing more with less.
∴ EFFICIENCY EPHEMERALIZES[11]

Fuller's 1960 bubble montage of the 2 mile (3.2 kilometer) diameter dome over Manhattan captured media attention, but it was not the first proposal for a large-scale environmental envelope. Earlier, the young German architect, Frei Otto, had proposed a "City in the Antarctic" under a large cable net roof, one of a number of unbuilt projects for human settlements in extreme climates that Otto pursued throughout his career. Reflecting on these studies, Otto reinforces Fuller's notion of the ephemeral as materially efficient and ecologically sustainable: "Our large-scale covering projects for the Arctic and our shade roofs in the desert were consciously utopian and planned as 'non-buildings.' The first ones date from 1951–52. I located them in extremely inhospitable areas in order to show that it was also possible to create paradisiacal environments there... I can only imagine such utopias being realized in an extremely lightweight form that does not burden the ground on which they stand in physical, chemical or visual terms and that can be removed without leaving a trace."[12]

At the Institute for Lightweight Structures in Stuttgart, which he founded in 1964, Otto articulated the principles and structural theory of all manner of lightweight structures and explored the potential of air as a structural element. Drawing from an understanding of biology, initially intuitive and empirical, then subsequently nurtured by close collaboration with the biologist Johann-Gerhard Helmcke in Stuttgart's Biology + Building research unit,

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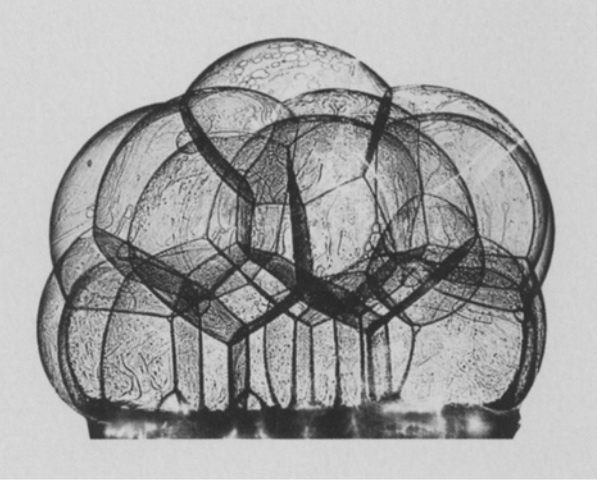

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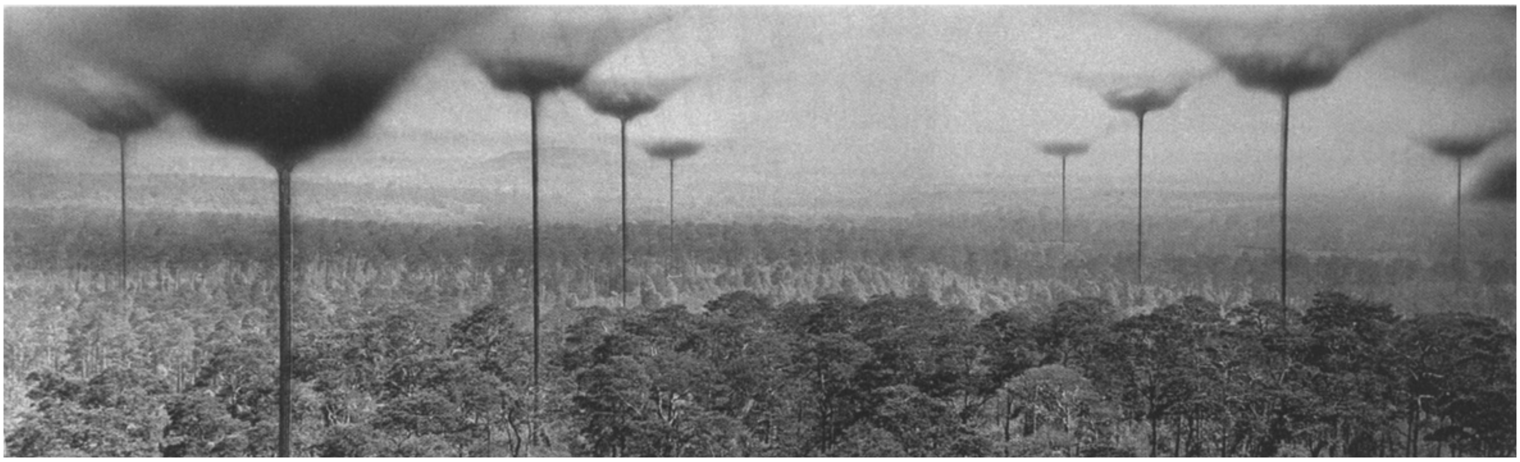
5__Buckminster Fuller's Manhattan bubble envisioned an urban scale climatic envelope. /
6__Frei Otto studied bubbles and pneus as natural structures of maximum efficiency. /

Otto concluded that all cells are fluid-filled membranes, either pneus filled with air or hydros filled with water. Form-finding experiments with soap film bubbles, natural pneus, were documented in his comprehensive treatise, *Zugbeanspruchte Konstruktionen* (Tensile Structures), published in 1962, which sought to "...promote air as the most lightweight of all building materials."[13]

For Otto, bubbles had not only structural and environmental implications but, through their identification with the ephemeral, were also politically freighted. His vision of "[a] gentle roof-like a cloudscape"[14] was a reaction against National Socialist preoccupations with monumental architecture some decades earlier and a response to the subsequent material destruction of World War II. As Winfried Nerdinger notes, both Sigfried Giedion and the Bauhaus celebrated the evolution of modern architecture as a process of dematerialization, "[b]ut other than Frei Otto, very few people developed a 'philosophy' of light weight construction with social connections. One who did was Buckminster Fuller, who defined the weight of buildings as a measure of the standard of development not just of industrialization, but also of mankind."[15] Like Fuller, Otto's work was focused as much on the psychology of "light-hearted improvisation"[16] as on the natural principles of lightweight construction. Just as Fuller's structural concepts proved to have parallels in nature, bubbles – as structures of maximum efficiency using a minimum of material – were prime exemplars of nature's economy of means. Although Otto researched bubbles extensively, his only realized pneumatic structure was a High Voltage Research Lab in Cologne, constructed in 1966.[17] More significant was the stream of proposals from 1941 onwards that, in addition to city-scale bubbles, included inflatable airplanes and "airfish," industrial sheds and convention halls. In schemes for vast air-supported greenhouses, his principles came full circle, synthesizing structure and enclosure with nature in a vision of a 20th century Eden.

Composite structures and variable skins

In addition to documenting Otto's own research, *Zugbeanspruchte Konstruktionen* is a compendium of inflated objects, buildings and structures ranging from sails, which he calls the oldest pneumatic structures, to paddling pools and satellites. Importantly, it includes two topics that



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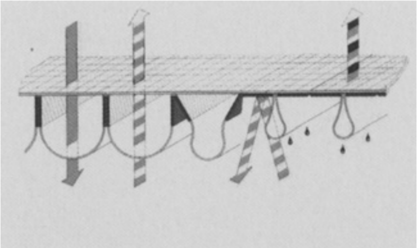

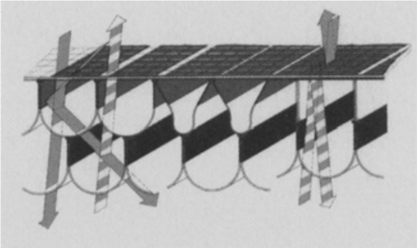

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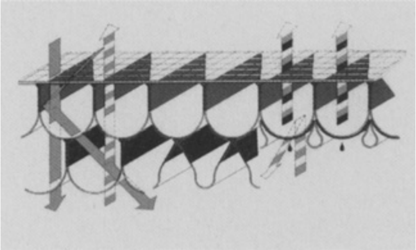

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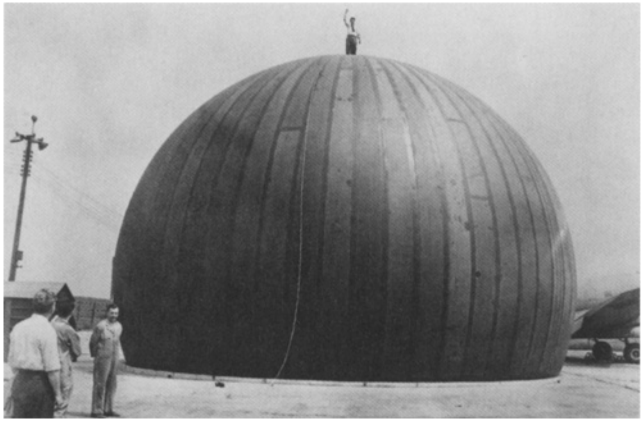
7__Frei Otto's 1965 study for an air-supported greenhouse enveloped nature on a vast scale. /
8–10__In the 1960s, physicist Nikolaus Laing proposed a series of multi layer film building skins with dynamic environmental performance controlled by variable air pressure.
8 Pneumatic wall in closed position on right turns a reflective surface to the outside.
9 Dual chamber system provides increased thermal insulation.
10 Dual chamber system closed on right to produce black body effect during the night. /

would, during the final decades of the century, become the most prominent areas of pneumatic exploration in architecture – cushion structures, or "pneumatically tensed envelopes that are closed on all sides and have a comparatively flat shape,"[18] and composite structures, which combine pneus with skeletons. Otto links composite structures directly to nature, observing: "The body structure of animals and human beings is a composite of rigid and compression-resistant members (bones, skeleton), surrounded by numerous tension elements such as sinews and membranes....The muscles are parcels of tissue enclosed by membranes. Since the tissues, whose individual cells are under blood pressure, exert a load on the enveloping membranes similar to that induced by a gas or liquid, it is not surprising that all tissue elements enclosed by membrane constitute pneumatically formable shapes, i.e., the obvious relationship of all pneumatic structures to these natural shapes is not accidental but inherent in the structure."[19]

At a colloquium held at the Institute for Lightweight Structures in 1967, the physicist Nikolaus Laing presented studies of a multi layer dynamic pneumatic envelope that could reduce the amount of terrestrial energy needed for heating and cooling. In the June 1968 issue of *Architectural Design*, Laing's moveable films, partly coated with metals, are described as capable of "...regulat[ing] precisely air temperature, light, humidity, rainfall and air circulation, with solar radiation as the only energy input, except for negligible amounts of subsidiary energy for control purposes (air pressure to deploy the membrane elements)." Suggesting that the culture of environmental fantasy of earlier centuries remained a vital force, the *AD* text concludes, "Tropical climates can be created in Newfoundland, and zero temperatures in the Sahara...extending the human habitat beyond the presently favoured regions. There could be one cheap and portable element combining all the functions of the usual climatic control environmongery."[20] It would be more than three decades before this concept of a thin film dynamic skin would be fully realized in long-life buildings.

Early pneumatic buildings

Although Buckminster Fuller and Frei Otto significantly advanced both the theory and propaganda promoting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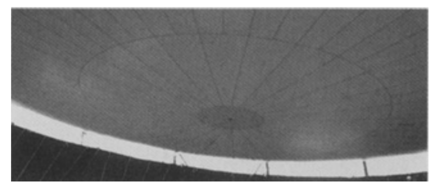
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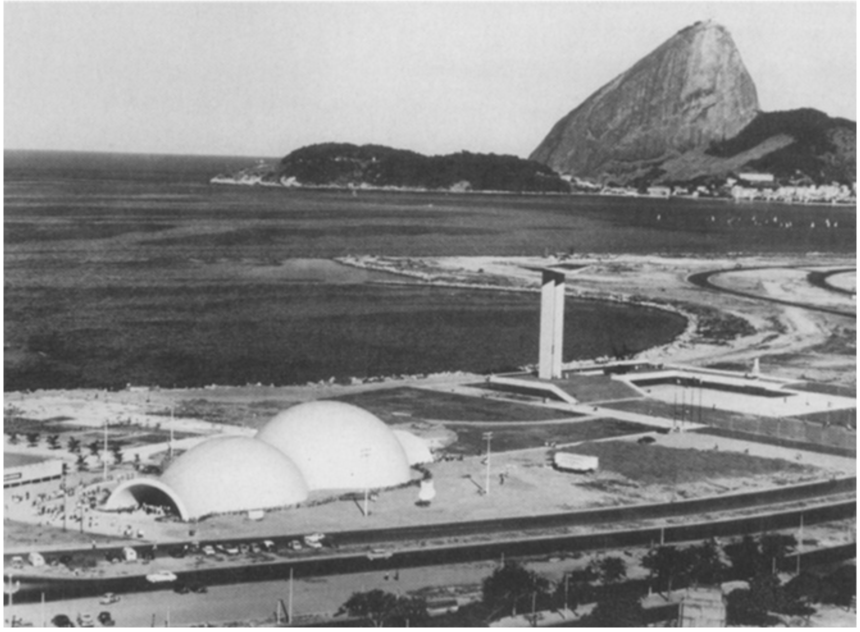
11__Walter Bird's radome prototype, developed in 1948 to shelter radar antennae from extreme Arctic environments, spawned numerous pneumatic structures for military applications. /
12–13__In 1957, *LIFE* magazine popularized Birdair's air-supported swimming pool enclosures as climatic envelopes. /
14–16__The 1959 Boston Arts Center Theater featured a 44 m diameter air-filled cushion held by a steel frame. /

pneumatic structures, others applied and commercialized these principles. The engineer Walter Bird, whose career began in research, is credited with realizing the first air-supported building structures. Working at the Cornell Aeronautical Lab, Bird successfully designed radar antennae as pneumatic cushion structures on steel rings.[21]
He was subsequently commissioned by the US Air Force in 1946 to design building enclosures for early warning radar antennae that were required to be portable and transparent to radar signals, while also providing shelter from harsh arctic environments. Following successful testing of prototypes for low-pressure air-supported radomes in 1948, over a hundred of these buildings were constructed during the 1950s using synthetic fibers like nylon and terylene coated with vinyl, neoprene or hypalon.[22] With the durability of pneumatic structures in extreme climates proven, Walter Bird set up the company Birdair Structures, Inc. in 1956 to continue to design inflatable antennae, towers and buildings for the military and to develop commercial applications for air-supported and tensile fabric structures. Walter Bird's environmental bubbles were popularized by pre-engineered pneumatic storage facilities, construction site shelters and greenhouses. His swimming pool enclosures, which featured on the cover of *LIFE* magazine in 1957, signaled increasing public acceptance of air architecture, and companies offering inflatable buildings as products proliferated both in the United States and Europe.

Architects also began to take notice. In 1959, architects Carl Koch and Margaret Ross, collaborating with the engineer Paul Weidlinger and Birdair, designed the Boston Arts Center Theater. The design team initially investigated pneumatic formwork for the construction of a concrete dome. However, with insufficient project funds to construct a permanent building, they turned to temporary structures. Because of the significant clear span required by the theater, they developed a composite pneumatic and skeletal structure, with a roof that was a 44 meter diameter air-filled cushion of vinyl-coated nylon fabric. This cushion, 6 meters thick at the center when inflated, was held in position by cables around the circumference, which were attached to a steel compression ring supported on steel columns.[23]

In the year 1960, a pavilion for the US Atomic Energy Commission's traveling exhibition in South America was



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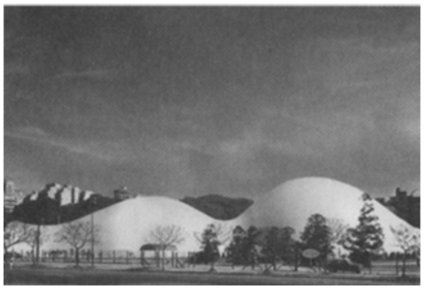

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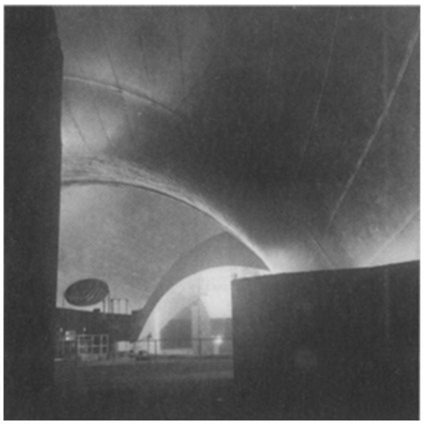

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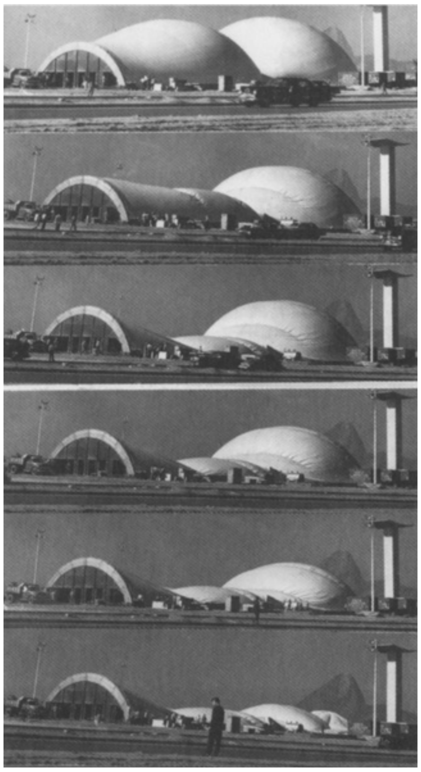
17–20__The air-filled and air-supported envelope of the US Atomic Energy Pavilion of 1960 was a study of continuous and complex curvature. /

hailed in *Architectural Forum* as "a great balloon for peaceful atoms."[24] It was designed by architect Victor Lundy in collaboration with Birdair; structural engineers Severud-Elstad-Krueger Associates; and mechanical engineers Cosentini Associates. Described by Reyner Banham as "the first great monument of environmental wind-baggery,"[25] this innovative volume with varying diameters of curvature was made of two skins, which were compartmented and independently pressurized to create a 1.2 meter thick air-filled insulating envelope. Due to safety and security concerns, the double skin was designed so that, if the outer skin was punctured or breached, damage would be limited to a single compartment and the pavilion would not collapse. This structure was a hybrid of an air-filled and air-supported envelope together with inflated self-supporting external canopies at the ends of the building, where rigid metal frames housed air lock doors. The building – 91 meters long, 38 meters wide and 19 meters high – was lightweight and portable. It could be transported in a container the size of a standard railway box car, erected in three to four days by a dozen untrained laborers without scaffolding, and fully inflated in 30 minutes.[26] Lundy went on to design further pneumatic structures for restaurants at the New York World's Fair in 1963–64.

Pop culture and the Space Race

The 1960s proved to be an effervescent decade for both pneumatic ideas and their applications. Reyner Banham, like Walter Bird, was trained and worked as an aeronautical engineer prior to becoming an architectural historian and chronicler of the avant-garde. His affinity for technology, developed as an engineer, combined with interests in pop and contemporary American culture, involving him with the Independent Group during the fifties. Banham articulated and supported "...radical critiques of the established orders of architecture, technology and society,"[27] in particular those that sought to advance the ephemeral, including ideas of Fuller and Otto, Archigram and Cedric Price in London, Haus Rucker Co. and Coop Himmelb(l)au in Vienna, and Utopie and the Situationists in Paris. Banham understood air-supported structures not as something new, but as having evolved from the history of patents like those recorded by Dunlop in 1888 for high-pressure tires and Lanchester in 1917 for low-pressure buildings. Character-



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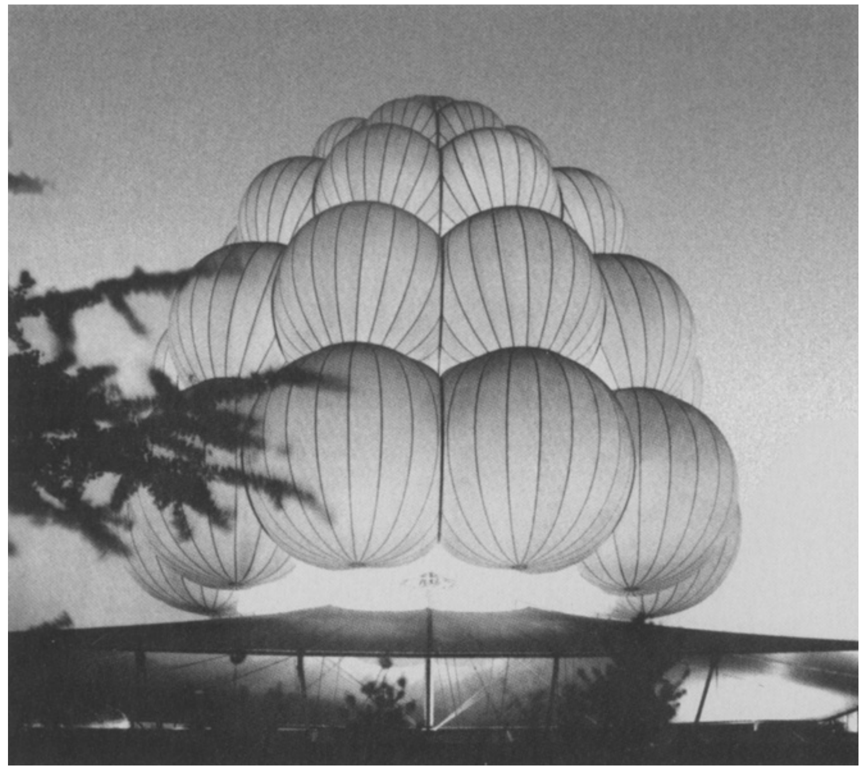

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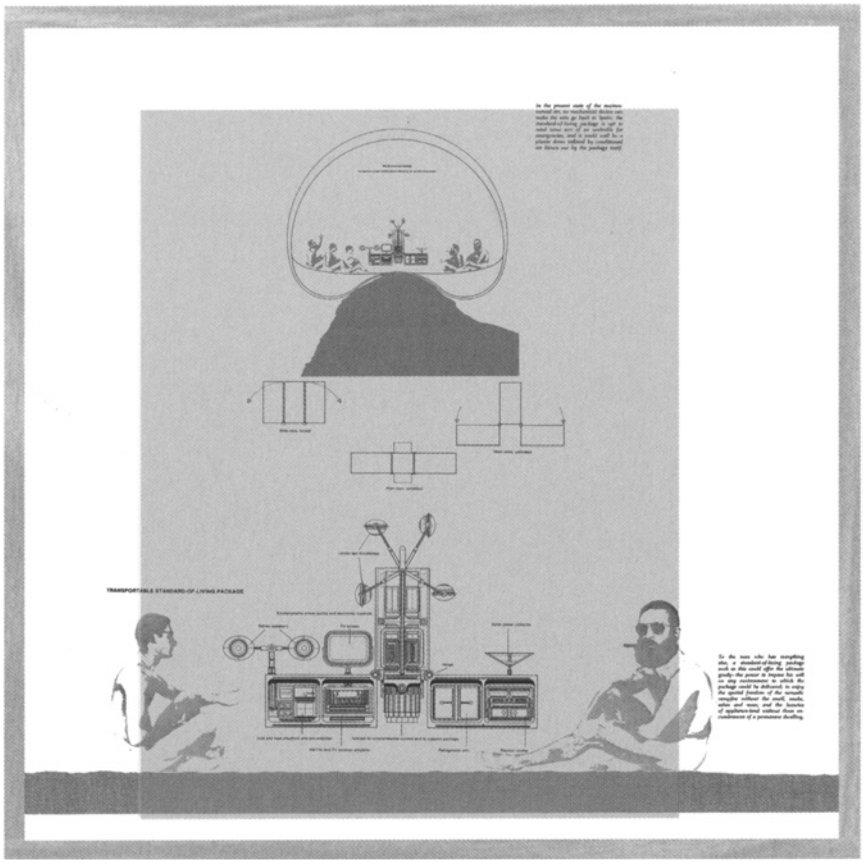
21–22__The rapid inflation of the US Atomic Energy Pavilion, which traveled throughout South America, was a public spectacle. /
23__Victor Lundy's Brass Rail Restaurant, New York World's Fair /

istically blurring distinctions between popular and high culture, he remarked, "The resistant, bouncing, sealed package of high-pressure air is familiar to anyone who ever had pretty balloons for Christmas, a spotted water-horse at the sea-side, an air-ring in hospital to prevent bed sores, or a 20th century wheeled vehicle. This sort of technology is the common property of most citizens of even moderately industrialized communities. But the low-pressure air-supported envelope is still so unfamiliar, even in advanced countries, as to be faintly alien."[28]

Banham was an advocate for the low-pressure inflatable experience, both in words and deeds, which he promoted as a technological Garden of Eden. His head was famously montaged onto François Dallegret's naked body in The Environment-Bubble drawing that accompanied his 1965 essay in *Art in America*, "A Home is not a House." In this essay, the house is dematerialized to a minimal but extensively serviced membrane, a shelter for a "power-point homesteading in a paradise garden of appliances."[29] Acting out this fantasy in 1968, his day-long occupation of an inflated plastic dome designed by Peter Murray and Tony Gwilliam was subsequently televised and published.

These forays into visual media were unusual for Banham, who was a consummate wordsmith. For images, he deferred to Archigram, whose name – a fusion of architecture and telegram – paid homage to Buckminster Fuller's propensity for inventing words and, reflecting Fuller's interest in shedding weight, was coined to lighten architectural discourse. The group developed themes explored by Fuller and Otto and, like Banham, connected them to pop culture. In addition to comic books and movie stars, Archigram was influenced by the work of the Independent Group, including exhibitions like "Man, Machine and Motion" at London's Institute for Contemporary Art in 1955, which featured photos and drawings of "...devices that had allowed humans to conquer land, sea, air and space."[30]

The US space program had a strong impact on Archigram's imagery. They were infatuated with the extensively serviced bubbles that were being designed both to explore space and to enable man to live in the harsh environment beyond Spaceship Earth. In addition to putting men in space and landing on the moon, the National Aeronautical and Space Administration (NASA) was busily developing



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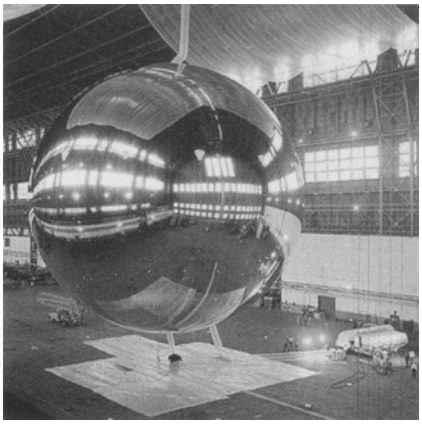

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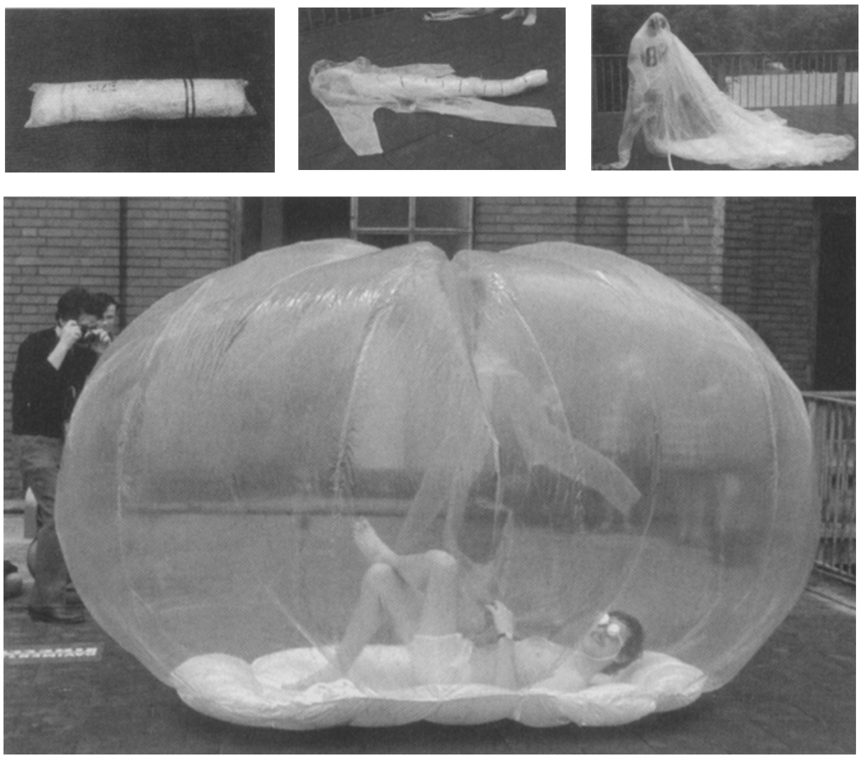
24__"The Environment-Bubble" drawing by François Dallegret imagined a bounded domain made habitable by technology. / 25__Echo I, a communications satellite launched by NASA in 1960, inflated in gravity-free space to form a 30 m diameter sphere. /

unmanned satellites for meteorological, communications and defense purposes. Instead of thinking of balloons as ephemeral, these "sataloons" married the inflatable character of balloons with the long life required of satellites. In 1960, Echo I, a 30 meter diameter passive communications satellite – made of transparent mylar foil only 0.127 millimeters thick and coated with aluminium vapors to increase its reflective properties – became the largest volume satellite that had been put into orbit. For launching, it was folded into a ball just over 1 meter in diameter. At the same time, NASA was testing Echo II, 41 meters in diameter and made of two leaves of aluminium foil bonded to mylar, which was 50 times more rigid than Echo I. NASA was also developing Rebound, a 61 meter diameter inflatable of the same laminate, but with windows chemically milled out of the aluminium layers to achieve a structure as strong as Echo II but 30 percent lighter. Reiterating Buckminster Fuller's equation of lightness with efficiency, a representative of NASA, testifying before the US Congress in 1961, explained the value of inflatable structures by noting, "...it takes many pounds of propellant to put one pound of payload into orbit. We all know this... Anything we can do to make the payload light is all to the good."[31] Also in the sixties, a new and larger generation of air-supported radomes by Birdair and others was built in the US and Europe to house the huge antennae needed for the Telstar program of global communications. The largest in Andover, Maine was 64 meters in diameter and was made of hypalon-coated Dacron fabric.[32]

Caught up in the aura and excitement of these space programs, Archigram produced a steady stream of visionary unbuilt projects that popularized the rapid technological progress of NASA and the military-industrial complex. For individuals, there were highly serviced "piped" environmental bubbles like the Cushicle and the Suitaloon – a linguistic offspring of NASA's sataloon – as well as the Inflatable Suit-Home that could operate either as clothing or as a room capsule. At the urban scale, Blow-out Village – a temporary enclave transported by hovercraft and featuring inflatable structural ribs with a clear plastic enclosure – was proposed for disaster relief, workmen in remote areas and "fun resorts" at festivals or the seaside.[33] Instant City was a vast mobile metropolitan bubble suspended from balloons and designed to graft onto existing city



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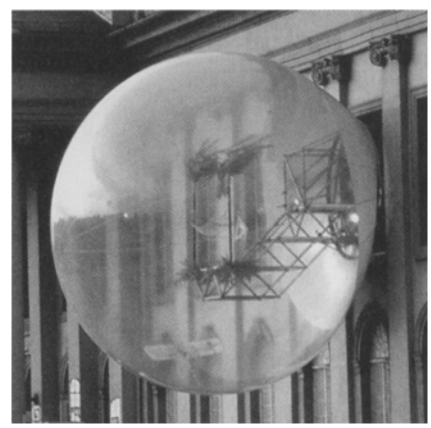

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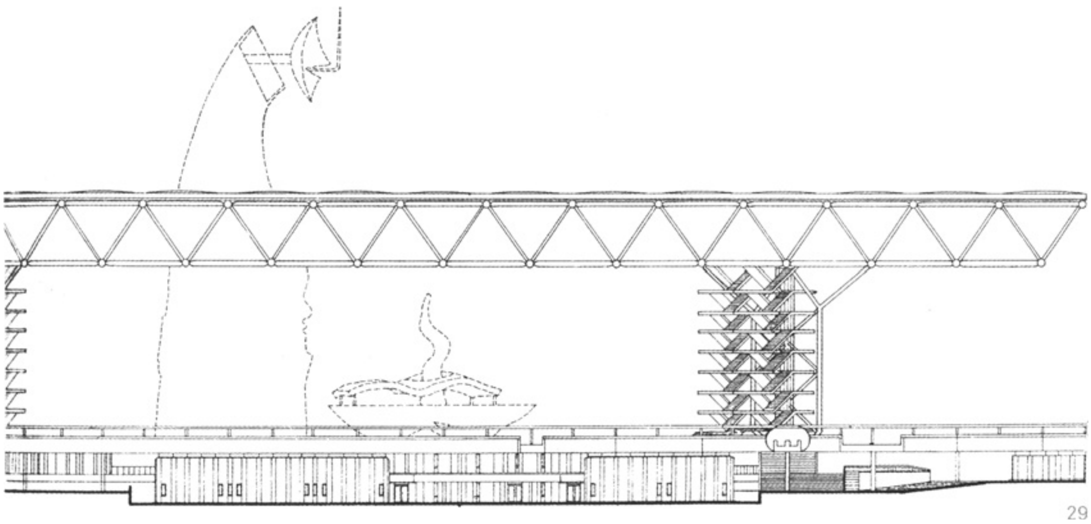
26__Archigram's Inflatable Suit-Home of 1968 proposed a well-serviced environment enclosed by a minimal membrane. / 27–28__In 1967, Haus Rucker Co. designed Oasis No. 7, a 7 m diameter inflated living cell. /

centers. All of Archigram's pneumatic proposals were, above all, spontaneous and ephemeral. Pop culture in turn reciprocated Archigram's adoration with inflatables featuring regularly in films and rock concerts.

Cultural critique

During the same decade, Haus Rucker Co. also explored pneumatic living cells that were provocatively posited in stark contrast to traditional monumental architecture, and which they imagined could aggregate to form cities. Likewise, Utopie, a group of architecture students at the École des Beaux Arts in Paris, proposed air-supported structures that aimed to redefine the discipline of architecture, moving it away from elitism, monumentality and permanence. Antoine Stinco, one of the group's core members, reflects, "...the 'inflatable' represented...a festive symbol of the new energy. It did so through its fragility, its will to express the ideas of lightness, mobility and obsolescence, through a joyous critique of gravity, of boredom with the world, and of the contemporary form of urbanism that had been realized."[34] This joyous critique of gravity, with its double entendre, was made manifest in "Structures Gonflables," a good-natured exhibition organized by Utopie and presented at the Musée d'Art Moderne in March 1968, which included vehicles, machines, tools and furniture, and works of art, architecture and engineering. Across the Atlantic, the "Air Art" exhibition at the Contemporary Art Center in Cincinnati included works by Andy Warhol, Les Levine and Hans Haacke, among others. In June 1968, *Architectural Design* in the UK published "Pneu World," an overview of inflatable architecture, lightweight paraphernalia and newly created consumer products. However, in Paris, this atmosphere of heady lightness and the liberation that it symbolized bubbled over onto the streets, just as it had done two centuries earlier. As Marc Dessauce notes, "Pneumatics and revolution agree well. Both are fueled by wind and the myth of transcendence; as the balloon enraptures the child, they animate and transport us on the promise of an imminent passage into a perfected future."[35] The Situationists, who were among the leaders of the student uprising in May 1968, rallied to the revolutionary cause by speaking, in terms strikingly similar to the words of Frei Otto, of "...ephemerality, of being 'in time,' and of a 'culture that would not leave a trace'..."[36]



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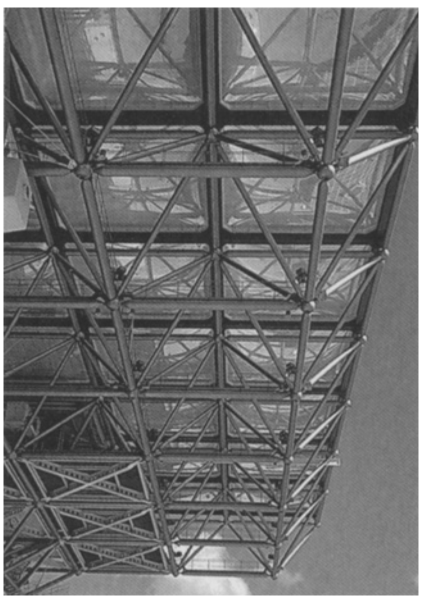

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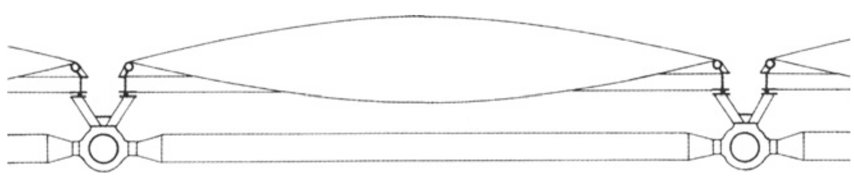

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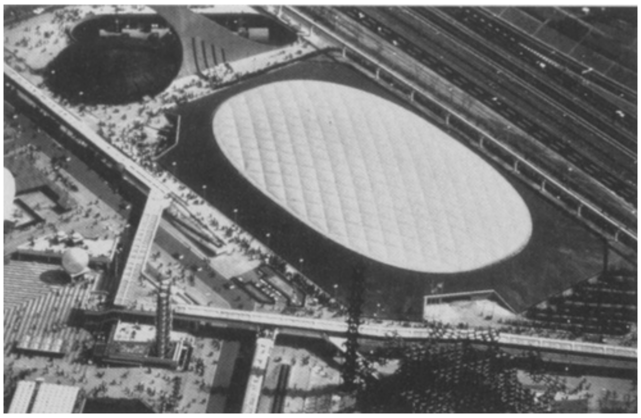
29–32_The roof of Festival Plaza designed by Kenzo Tange for Expo 70 in Osaka had a steel frame clad with air-filled cushions that featured moveable films governed by variable air pressure. /

Exhibitionism

The decade culminated with Expo 70 in Osaka, arguably the largest ever collection of air-supported structures that "...signaled the integration and institutionalization of the inflatable spectacular."[37] Using the same principle as the inflated goatskins of Assyrian warriors some 2500 years before, a floating theater designed by architect Yukata Murata and engineer Manoru Kawaguchi was supported by buoyancy bags that were automatically adjusted to respond to audience load and movements.[38] The roof of Festival Plaza, designed by Kenzo Tange, drew upon Frei Otto's concept of composite structures, combining a steel space frame skeleton with an air-filled cushion skin. The two membranes of the large 10.8 meter square (116.6 square meters) translucent cushions consisted of multiple layers of polyester film, each playing particular weather protection, heat reflecting and loadbearing roles.[39] With variable air pressure to deal with changing weather, this roof was a harbinger of the development of current cushion envelope systems.

Another structure that was to have significant impact was the US Pavilion, which was designed by architects Davis, Brody, Chermayeff, Geismar and De Harak working in collaboration with structural engineer David Geiger, Birdair and fabricators Ohbayashi-Gumi and Taiyo Kogyo in Japan. The pavilion paid homage to the unbuilt schemes of Lanchester and Stevens some 30 years earlier. It featured an enormous clear span structure 142 meters long and 83.5 meters wide with a lightweight air-supported envelope of translucent white vinyl-coated glass fiber fabric – originally developed for astronaut space suits – that was tethered by a net of steel cables.

To avoid deflection at the center, which could cause ponding and structural failure, it was decided not to have cables radiating from a central tension ring. Instead, they were arranged in a diamond grid, which reduced the weight of the cables by 33 percent compared to a rectangular grid. The cables were anchored in a reinforced concrete compression ring with sufficient mass to prevent uplift. Rather than being tied into the ground, the compression ring was separated from the concrete base by a galvanized steel sheet so that it could slide to dampen the motion of the cables and roof in normal windy conditions, yet remain stable even under typhoon and seismic loadings.[40]



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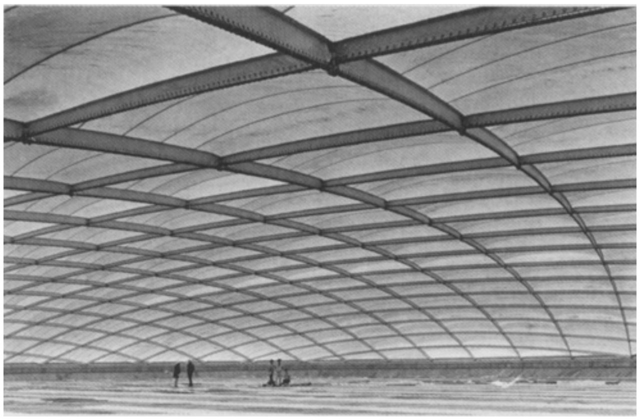

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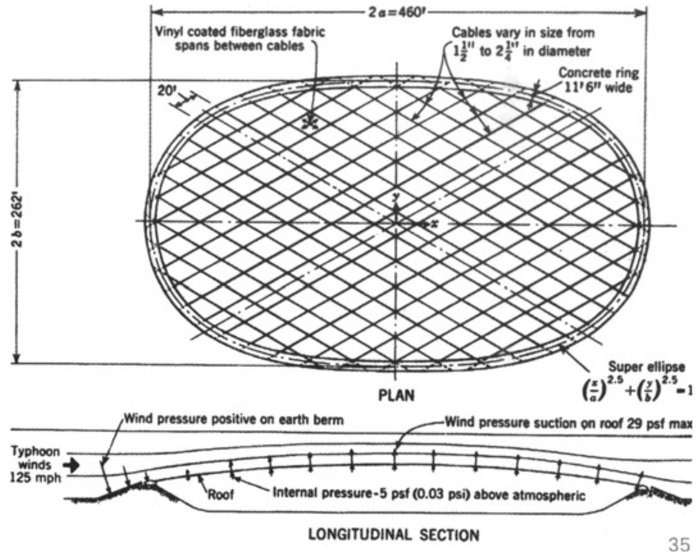

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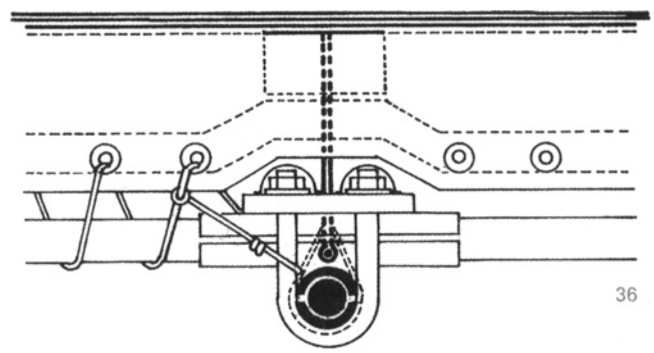

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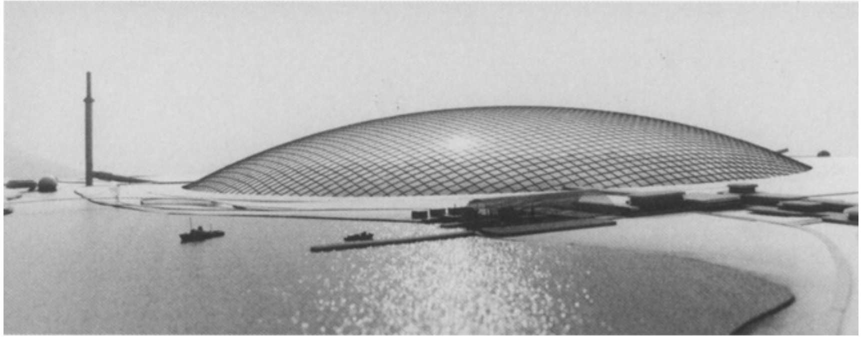
33–34__The US Pavilion at Expo 70 in Osaka was an elegant air-supported membrane tethered by a cable net. /
35__Plan and longitudinal section /
36__Skirts of the membrane material were laced to the cable net. /

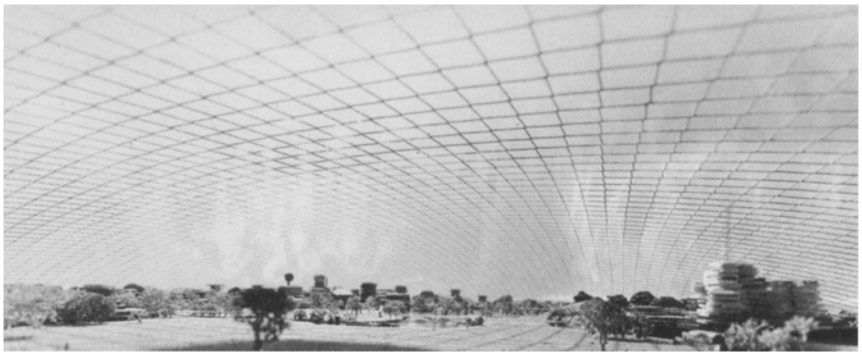
The low-pressure structure, entered through air locks, was irreverently described by the critic Peter Blake as "the biggest bunion pad ever – a sort of Oldenburg tribute to Dr. Scholl."[41] This air-supported roof, at 4.9 kilograms per square meter (one pound per square foot), was one hundredth of the weight and half the cost of Buckminster Fuller's smaller 77 meter diameter geodesic dome in Montreal, built just three years earlier.[42] Reflecting upon the dramatically increased efficiency of this ephemeral structure, engineer David Geiger commented, "There appears to be no maximum span for application of this type of roof..."[43]

Extra large and small

Indeed, following Expo 70, Birdair developed a proposal for an air-supported cable dome with a 300 meter span, and ideas for urban-scale bubbles proliferated. Davis Brody proposed a covered arctic city for a World Environmental Laboratory with an air-supported membrane spanning nearly 2500 meters.[44] In 1971, Frei Otto – collaborating with Kenzo Tange, Ted Happold at Ove Arup and Farbwerke Hoechst AG – published a proposal for a covered arctic city for 45,000 people in the mining industry. The harsh environment was to be made habitable by a shallow domed, air-supported envelope comprising two sheets of transparent synthetic material restrained by a polyester cable net with a clear span of 2000 meters.[45] And in 1980, architect Arni Fullerton, Frei Otto and Buro Happold collaborated on 58 Degrees North, a commission from the Canadian government for a covered city in the Artic for 10,000 workers engaged in extracting petroleum from tar sands in Alberta. While Otto proposed a fabric roof supported by masts and cables, Buro Happold put forward a scheme with an air-supported structure. One of their options for the membrane of the clear-span, cable-restrained elliptical roof, approximately 300 x 550 meters, was air-filled cushions of ETFE (ethylene tetrafluoroethylene), a new material.[46] Although this particular project was not realized, ETFE would emerge to play a pivotal role in the evolution of pneumatic structures.

In addition to inspiring these unbuilt projects, the achievements of Osaka paved the way for a series of very large air-supported stadium enclosures built on the same structural principle as the US Pavilion. These included the





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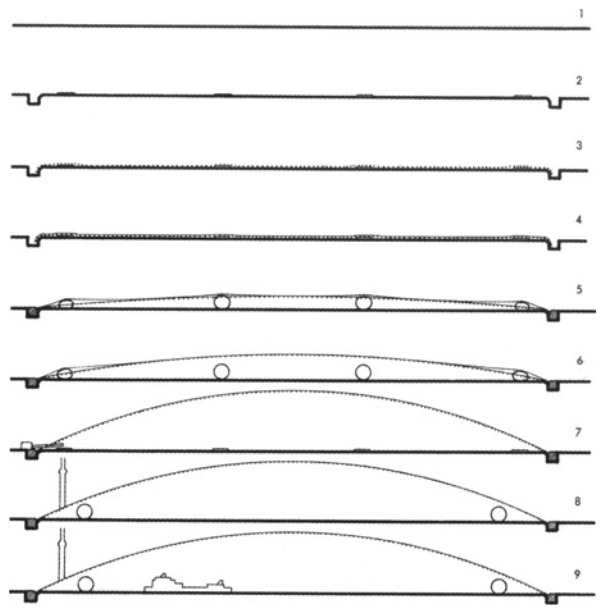

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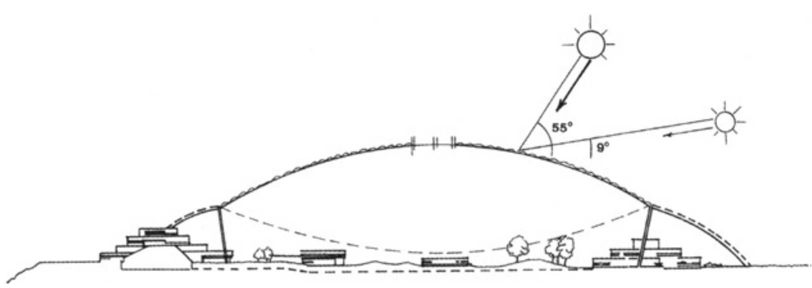

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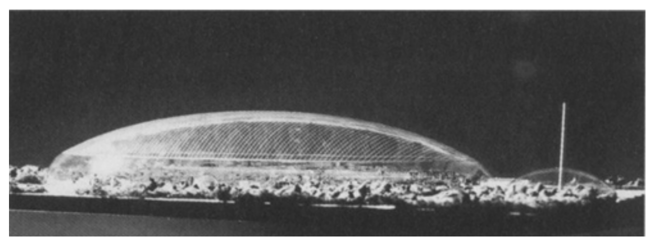

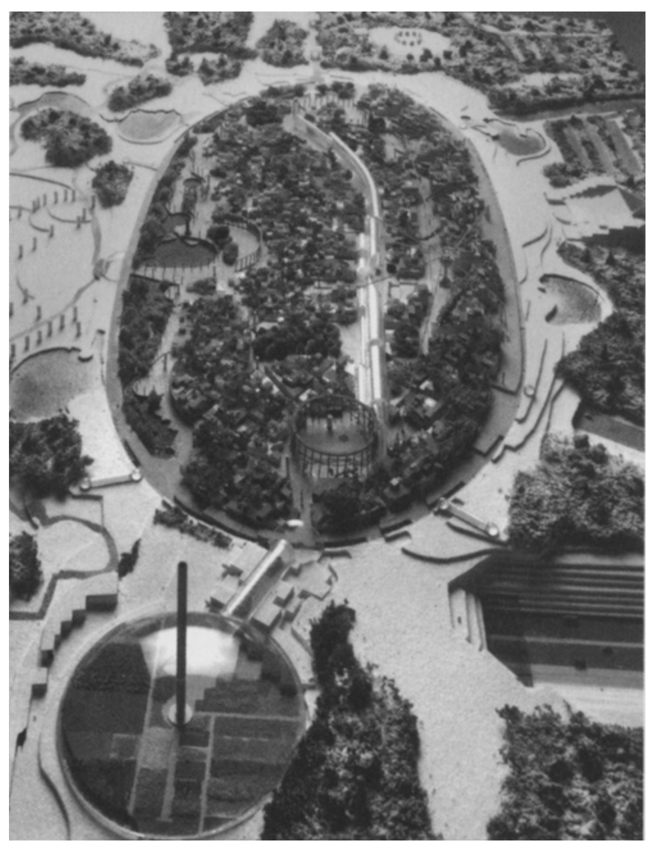

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37–38__A City in the Arctic, proposed in 1971, created a habitable environment within an air-supported, cable-restrained envelope spanning 2000 m. /
39__The suggested erection technique used balloons to assist with the initial lifting of the membrane off the ground. /
40–42__One cladding option for the air-supported, cable-restrained membrane of 58 Degrees North, an arctic city scheme designed in 1980, was two layer cushions of ETFE. /

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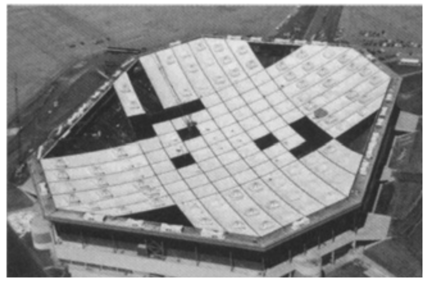

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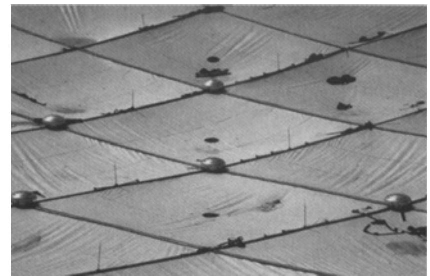

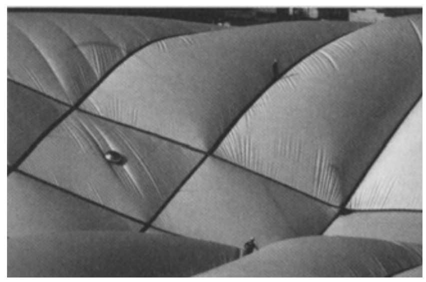

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43–47__This original Teflon-coated fiberglass membrane covering the 1975 Pontiac Silverdome was air-supported but, following damage by snow in 1985, was replaced by fabric on a steel frame. /

1975 Pontiac Silverdome near Detroit and the 1982 Hubert H. Humphrey Metrodome in Minneapolis, both made of Teflon-coated fiberglass. Relying on the air lock for stability, however, this genre lost popularity because of structural problems arising from varying air pressure during severe storms and loss of air pressure caused by punctures from heavy snow loads.

On a more modest scale, temporary offices for Computer Technology Limited by Foster Associates, constructed in 1970, helped to change the image of inflatable architecture, "[extending] the boundaries of pneumatics far beyond mere industrial and sporting enclosures on the one hand and exhibition fantasies on the other."[47] Although it was conceived as a pragmatic temporary building, this scheme gave new life to the pneumatic imagination. Eager for innovation and seeking lightness, Foster looked to the aerospace industry, observing that "...the Farnborough Air Show, with its vast array of sub-contractors and exhibits, provides more hard-edged clues and inspiration than this year's Sweets Catalog."[48] In 1968, Foster had also begun collaborating with Buckminster Fuller on a series of projects. The Climatroffice of 1971 – a descendent in name of the Fuller-inspired geodesic Climatron of 1960 – explored multi-story mixed-use spaces with planted roofs, all within a total microclimate enclosed by a large, transparent clear span envelope. Recalling Loudon's early 19th century claims for man's mastery of nature, Banham summed up the potential manifested in these and other early Foster projects as "the possibility of bending the environment to one's will through high technology," adding that "...the proof is in the performance."[49] Again, it would be several decades before these ideas were realized.

In the 1980s, in place of air-supported structures, attention shifted to air-filled cushion envelopes as a consequence of the adoption of composite structural strategies, advances in material science and, perhaps most surprising given its pedigree as a transient, the evolution of the ephemeral bubble into more enduring forms of architecture. As environmental issues gained increasing prominence, it seemed that, once again, paradise had met payload, and the idea of the large-scale, lightweight environmental bubble was still alive and well.

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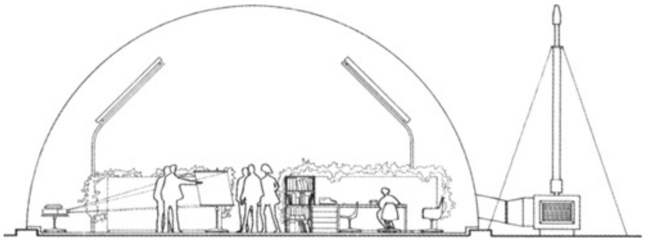

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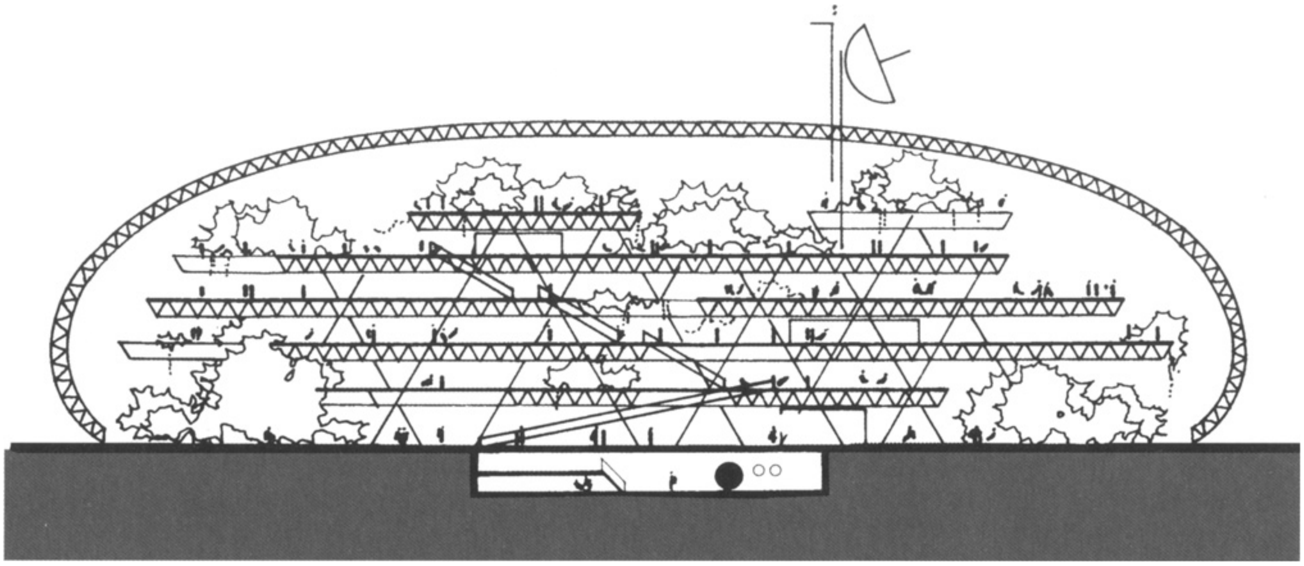
48–49__Although a temporary building, air-supported offices for Computer Technology, designed by Foster Associates in 1970, opened the door for broader and more permanent architectural applications of inflated structures. /

1__ Roger N. Dent. *Principles of Pneumatic Architecture* (New York: Halstead Press Division, John Wiley + Sons, Inc.) 1972, p. 27.
2__ Marc Dessauce, editor. *The Inflatable Moment* (New York: Princeton Architectural Press and The Architectural League of New York) 1999, p. 128.
3__ Joachim Krausse and Claude Lichtenstein, editors. *Your Private Sky* (Baden: Lars Müller Publishers) 1999, p. 33. Fuller's phrase was subsequently borrowed by Disney to name a ride at EPCOT (Experimental Community of Tomorrow), a theme park that opened in 1982. EPCOT was originally conceived as a utopian experiment proposed by Walt Disney in the 1960s but never realized. Instead it became a theme park that used a Buckminster Fuller-inspired geosphere as its icon.
4__ Id. at p. 135, as quoted from the June 1929 issue of *Architecture,* p. 339.
5__ Id. at p. 442.
6__ Id. at p. 354.
7__ Frei Otto. *Tensile Structures* (Cambridge: MIT Press) Fifth printing 1982, p. 115.
8__ Dent, op. cit.,p. 38.
9__ Krausse and Lichtenstein, op. cit., p. 412.
10_ Id. at p. 453.
11_ R. Buckminster Fuller. *Nine Chains to the Moon* (Garden City: Anchor Books) 1971, p. 259.
12_ Winfried Nerdinger. *Frei Otto Complete Works* (Basel, Boston, Berlin: Birkhauser) 2005, p. 144.
13_ Id. at p. 189.
14_ Id. at p. 11.
15_ Ibid.
16_ Ibid.
17_ Id. at p. 240.
18_ Otto, op. cit., p. 106.
19_ Id. at p. 148.
20_ "Pneu World," *Architectural Design* (June 1968) p. 267.
21_ Otto, op. cit., p. 110.
22_ Dent, op. cit., p. 35.
23_ Id. at p. 40.
24_ David Allison "A great balloon for peaceful atoms," *Architectural Forum* (November 1960) p. 142.
25_ Dessauce, op. cit., p. 31.
26_ David Allison, op. cit., p. 145.
27_ Reyner Banham. *Age of the Masters* (New York, Evanston, San Francisco, London: Harper + Row Publishers) 1975, p. 133.
28_ Dessauce, op. cit., p. 32. "Monumental Wind-bags" was originally published in *New Society*, April 1968.
29_ Joan Ockman, editor. *Architecture Culture 1943–1968* (New York: Rizzoli/Columbia Books on Architecture) 1993, p. 377.
30_ Simon Sadler. *Archigram: Architecture Without Architecture* (Cambridge and London: MIT Books) 2005, p. 38.
31_ *Inflatable Structures in Space, Hearing before the Committee on Science and Aeronautics, US House of Representatives* (Washington DC: US Government Printing Office) 1961, p. 5.
32_ Dent, op. cit., p. 196.
33_ Peter Cook, editor. *Archigram* (New York: Princeton Architectural Press) 1999, p. 61.
34_ Dessauce, op. cit., p. 71.
35_ Id. at p. 13.
36_ Id. at p. 18.
37_ Id. at p. 145.
38_ Dent, op. cit., p. 218.
39_ Thomas Herzog. *Pneumatic Structures – A Handbook of Inflatable Architecture* (New York: Oxford University Press) 1976, p. 48.
40_ David Geiger. "US Pavilion at Expo 70 features air-supported cable roof,"



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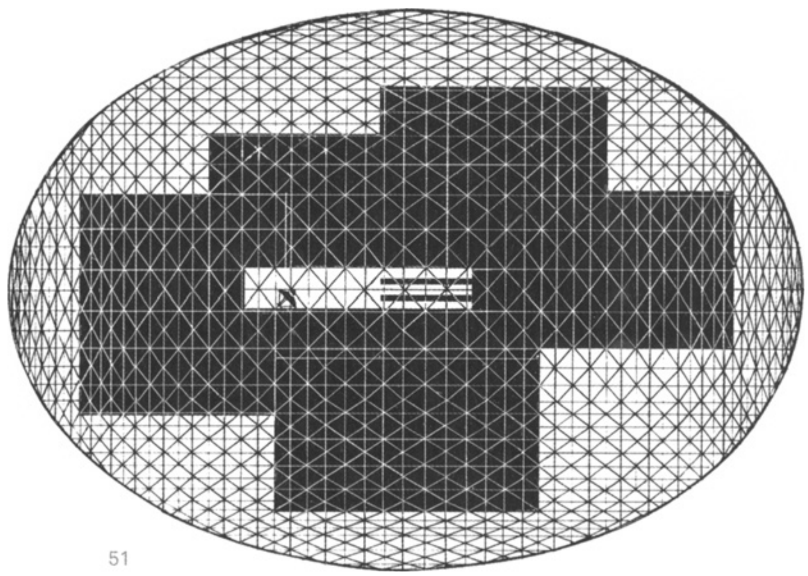

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50–51__Climatroffice, a 1971 collaboration between Buckminster Fuller and Foster Associates, proposed a large mixed-use building and landscape within a climatic envelope. /

Civil Engineering – ACSE (March 1970) pp. 48–50.
41_ Dessauce, op. cit., p. 145.
42_ Dent, op. cit., p. 211. Geiger, op. cit., p. 48 and 50.
43_ Geiger, op. cit., p. 50.
44_ Hix, op. cit., p. 193.
45_ Nerdinger, op. cit., p. 280.
46_ Ian Liddell. "A covered Northern Township, Alberta," *Patterns 1* (October 1987) pp. 16–17.
47_ Dent, op. cit., p. 192.
48_ *Foster Associates* (London: RIBA Publications Ltd.) 1979, p. 10.
49_ Id. at p. 8.

Material Matters

ETFE

ETFE (ethylene tetrafluoroethylene) is a man-made fluoropolymer. Its principal ingredient is fluorite, a common mineral, which is combined with hydrogen sulphate and trichloromethane. These ingredients make chlorodifluoromethane, that by pyrolysis, yields tetrafluourethylene (TFE), a colorless, odorless gas that is joined with ethylene to make the ETFE copolymer. ETFE resin is produced either in powder form or compressed into pellets.

Development and early architectural applications

ETFE has been known since the 1940s, when a US patent for the substance was granted to DuPont.[1] Unlike its close relation Teflon (PTFE), which was an accidental spin-off, ETFE was the result of DuPont's research program to develop an insulation material for industrial machinery that was resistant to friction and abrasion, immune to radiation and effective at both extremely high and low temperatures. It was not commercialized until 1970, when DuPont in the US and Hoechst in Germany launched ETFE wire and cable insulation, which found a wide range of applications in the petroleum, automotive, aerospace and nuclear industries. ETFE is also used in the chemical industry, where, as one of the most stable known chemical compounds, it has been widely adopted for applications in hostile environments, such as filters and linings for acid and alkaline baths. Formed for these purposes by injection molding, hot dipping or spraying and baking, ETFE resin can assume an infinite array of forms.[2]

Architectural interest in ETFE was sparked by the first oil crisis in 1973–74, when Europe began to focus on harvesting solar energy to replace fossil fuels. Extruded ETFE film was developed at Hoechst, where researchers significantly advanced production techniques and market applications, including use as a replacement for glass in greenhouses and, in metallized form, for thermal solar collectors. Realizing the potential benefits of this material that weighs only a fraction of glass, and which, for greenhouses, can produce food with the same color and flavor as when grown in the open air, Hoechst submitted ETFE to weathering tests both in Germany and in Arizona. In 1984, after a decade of field testing, ETFE showed no change in its optical or mechanical properties, and these results provided the assurance that paved the way for architectural applications.

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1__Fluorite, a common mineral, is the main ingredient in the production of ETFE. /

Mangrove Hall, Burgers' Zoo, Arnhem
ABT Adviesbureau voor Bouwtechniek, 1982 /
2__ETFE's architectural debut was as a replacement for FEP cushions that failed due to creep and tear propagation. /

The architectural use of ETFE films was pioneered by Vector Foiltec in Bremen. The first applications were for plant houses at Burgers' Zoo in Arnhem in the Netherlands. Vector Foiltec, at the time a sailmaker for yachts, was contacted in 1982 to rectify a building failure. Shortly after completion, the original cable-supported FEP (fluorinated ethylene-propylene) envelope of the Mangrove Hall in Arnhem collapsed, a result of FEP's tendency to creep, become thin and rapidly propagate tears. In lieu of the three 45 meter long FEP cushions of the original enclosure, the ETFE replacement – stronger, lighter and resistant to tear propagation – is configured as 45 smaller cushions with lower air pressure than their predecessors. Reusing the original steel mast and cable structure, the three layer ETFE cushions provide a well insulated environment flooded with daylight in which mangroves thrive. The success of this effort led Burgers' Zoo to commission two further ETFE buildings. The Tropical Hall, completed in 1988, introduced the concept of the large self-sustaining ecosystem that requires no pesticides and was followed by the Desert Hall in 1993. These buildings transformed the zoo experience in Arnhem, quadrupling visitor numbers.

Vector Foiltec, with extensive knowledge of high performance foils and fabrics for the sails of international racing yachts, went on to develop the engineering protocols needed to use inflated ETFE cushions as architectural cladding and designed and built production machinery for cutting and welding ETFE film. In addition to buildings for plants, leisure park pools for human beings provided a significant early and enduring architectural market for ETFE, which is immune to corrosion in these high humidity chlorinated environments. With Europeans having significant amounts of holiday time but not always the financial resources to travel to the sunshine, ETFE pool enclosures for Centre Parks and other resort chains sought to bring a Mediterranean climate to northern Europe.

ETFE is resistant to degradation both from ultraviolet light and atmospheric pollution. It exhibits less than a 10 percent decrease in material strength after 10,000 hours of concentrated artificial weathering,[3] an effect that is offset by a similar increase in strength due to wind-generated molecular realignment. With up to 30 years of exposure at natural test sites in Germany and in Florida in the United States – an environment with salt water, high humidity and

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3–4__Mangrove Hall interior and roof /

Desert Hall, Burgers' Zoo, Arnhem
ABT Adviesbureau voor Bouwtechniek, 1993 /
5–6__The Desert Hall, together with the Mangrove and Tropical Halls, transformed the zoo experience. /

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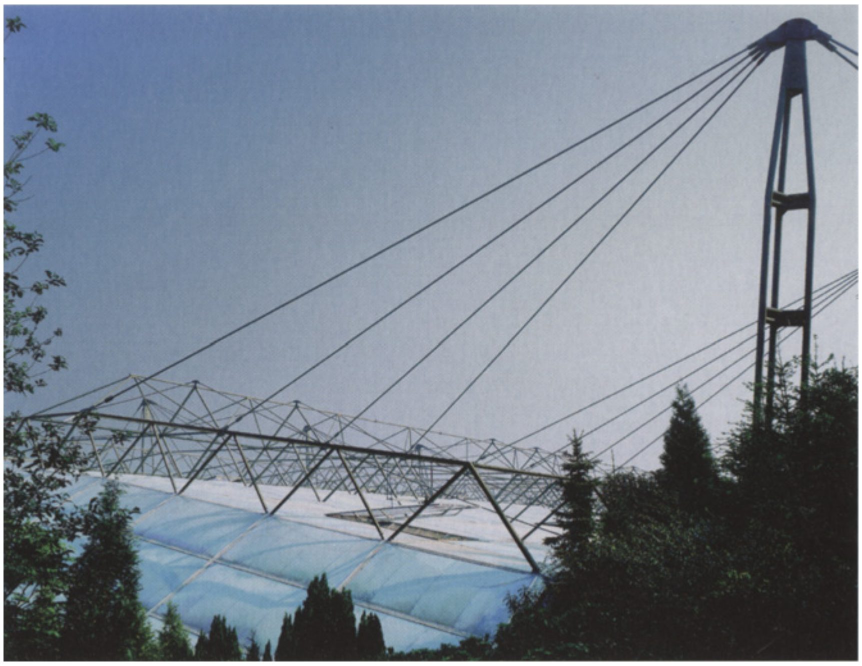

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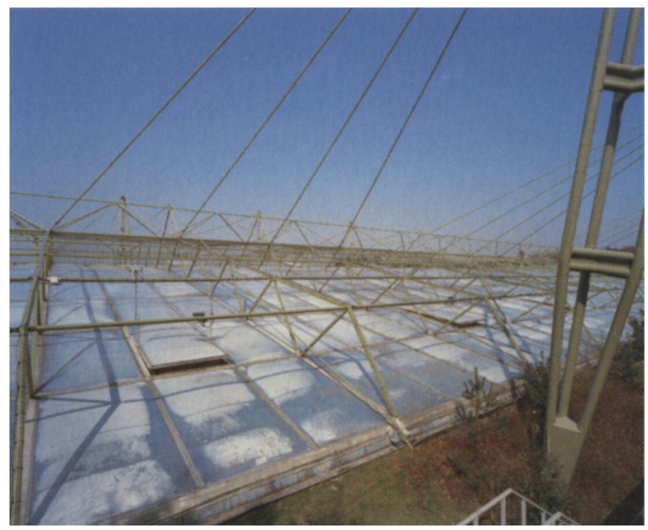

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Tropical Hall, Burgers' Zoo, Arnhem
ABT Adviesbureau voor Bouwtechniek, 1988 /
7–9__Supported by cable-stayed external steel trusses, an ETFE cushion envelope has enabled the tropical ecosystem within to be self-sustaining without pesticides. /

strong ultraviolet light – ETFE has suffered no perceptible adverse effects. It does not become brittle, nor does it discolor or deteriorate. Importantly, this durability is intrinsic to ETFE, not the result of applied coatings that could themselves be vulnerable to decay. As a relatively new material, ETFE's life expectancy is unknown, but with no evidence of degradation to date, it is well on its way to aquiring the credentials for belonging in the stable of durable long-life materials.

Film production and printing

From the outset, ETFE film has been either blown or extruded. In both processes, ETFE resin is heated to temperatures in excess of 380 degrees Celsius to reach a molten state. Blown film is made with a ring dye, which creates a cylindrical form that, when cut and opened flat, produces up to 5 meter wide foil. Although the production line is less costly than for extruded film, the optical quality and tolerance of blown film are inferior. Its principal application is therefore in greenhouses. For extruded film, more costly to produce and higher in quality, the molten resin is passed between rollers, which extrude a film that is typically 1530 millimeters wide. Asahi, the current market leader in ETFE film production, has recently developed a new production line to make 2200 millimeter wide film, a development made economically viable by the strong market for greenhouse construction in Japan. The extruded film, cooled by passing over a series of rollers, is wound onto cardboard tubes for storage and transportation. ETFE foils are currently manufactured under a number of trade names in Japan, the United States, Italy, Germany, Britain and the Netherlands. Fabricators specify foils in terms of color; transparency, translucency or opacity; either a matt or shiny surface; and thickness, which varies from 50 to 250 microns (1 micron = 1/1000 millimeter). For a single project, fabricators might purchase foils from a range of manufacturers. Given the consistency of the material it is not necessary to test each roll prior to fabrication, although continuous measurement of thickness and chemical purity is undertaken.

ETFE films may be used as extruded or with printed patterns applied to the surface. To create chemically bonded adhesion, the molecular structure of the film's very smooth surface must be opened up. Corona treatment by

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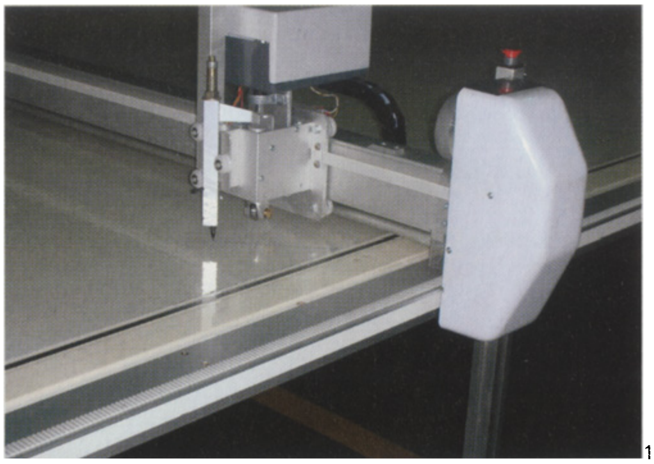

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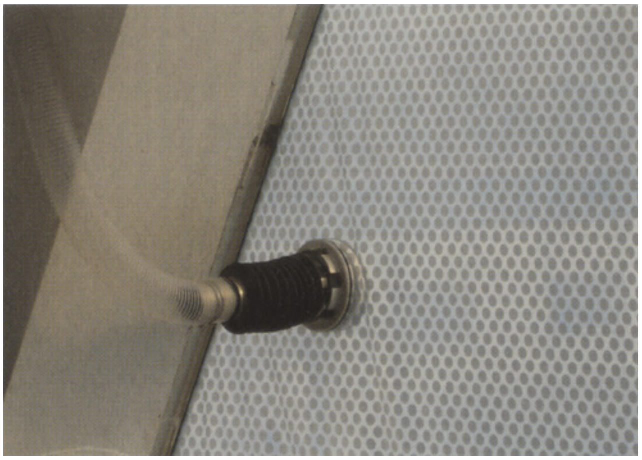
10__The fabrication of ETFE cushion envelopes combines handcraft with digital technology. /
11__Each layer of ETFE foil is individually cut by a CNC blade. /
12__The drop bar welder, developed by and proprietary to Vector Foiltec, welds ETFE using a precision controlled combination of heat, pressure and duration. /

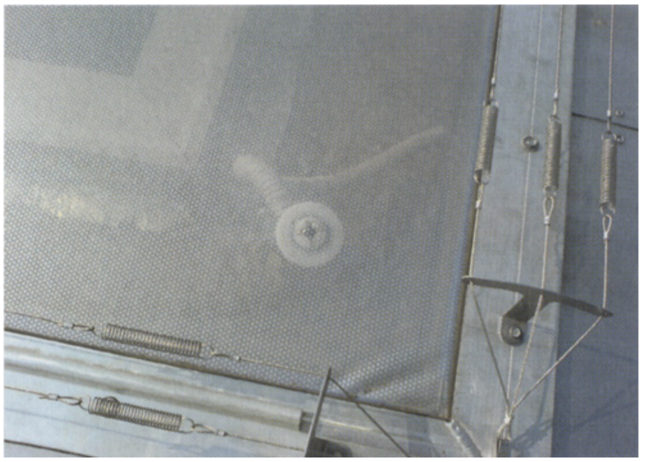
chemical application, electrical discharge or subjecting the film to high intensity radiation provides this molecular key for printing. Patterns are printed with opaque or translucent fluoropolymer inks, leaving approximately 50 millimeters clear along both long edges of the film for welds. The most common pigment is silver, typically used to reflect solar light and heat.

Fabrication

The fabrication of ETFE cushion envelopes, like sailmaking, combines high technology with handcraft. For cushion design, a range of non-linear analysis software packages is used and customized. ETFE cushions can be made in any size and shape. A typical assembly comprises two to five layers of foil of varying thicknesses. The foil is cut into lengths that are welded together to create the large surface areas of the cushions. The shape of each length is determined by proprietary software that unfolds the desired three-dimensional forms of the cushions into flat cutting patterns. This patterning helps to achieve the cushion camber by increasing the length of its diagonal. Digital design data feeds directly to a rotating CNC blade that can cut curved and irregular edges as easily as straight lines. Only one layer of foil is cut at a time. Lasers, although precise, are not used to cut ETFE because their very high temperature is inefficient for such a thin material and, at temperatures above 800 degrees Celsius produced by lasers, ETFE emits toxic fumes.

In multi layer cushions, the outer layer has more curvature to resist wind loads, while inner layers are progressively flatter. Notwithstanding these differences, the edges of each layer must be the same length to form the cushion. In the same way as software for fabric structures understands the difference between warp and weft behavior and between the cut form and the stressed form, the analysis of ETFE cushion structures needs to take account of the material's isotropic yield characteristics, bearing in mind that the final designed form is often only realized several years following erection when the building envelope has been subjected to changing temperatures and dynamic wind, rain and snow loads. Unlike fabric structures, which are essentially rigid when stressed, the final curvature of foil cushions is a combination of cutting and yield patterning.





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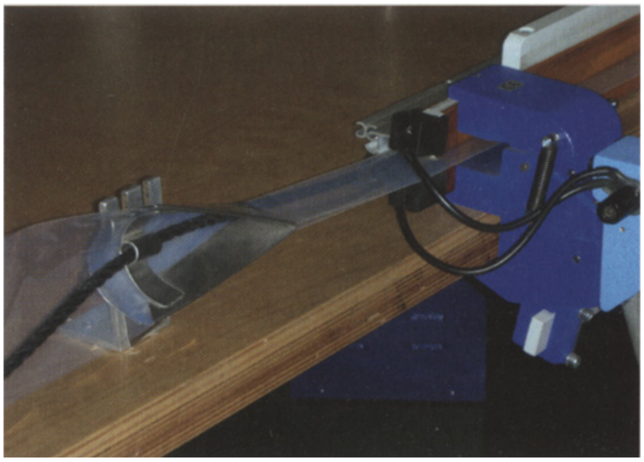
13__Injection-molded ETFE air valves, installed in cushions in the factory, are connected with flexible feeds to a plenum system. /
14__Most birds cannot gain a footing on ETFE cushions, and wires mounted on V-shaped brackets keep them off of the perimeter extrusions. /
15__A full-scale mock-up tests patterning. /

From the cutting tables, foils are manually transferred to welding tables. Typically, there are two production lines, one for 90 degree angles and another for all other shapes. Welds have a 10–15 millimeter overlap and are approximately 5 millimeters wide. A 1 millimeter wide weld is sufficient for strength and a good seal, so a considerable margin of safety is built into the system. Melt bond welding fuses two pieces of ETFE by the carefully controlled combination of heat, pressure and duration, with the stability of the process over time a critical factor to avoid overheating. No other material or chemical agent is required. Welding may be done by a wheel, which can do straight or curved seams at a rate of approximately 12 meters per five minutes, or by a drop bar, which does only straight lines, achieving the same length in a matter of seconds. Following the weld, excess material is trimmed by hand with scissors. The cushion foils are assembled manually so that all layers can be simultaneously trimmed and welded to form the cushion's keder edge. Finally, bespoke air valves are installed in the foil surfaces and sealed. The completed cushion is carefully folded to avoid wrinkling the films and wrapped in protective casing for shipping.

ETFE is costed by weight, typically measured in tons. As delivered to the factory, extruded and printed, ETFE foil is approximately the same square meter cost as tensile fabric and nearly 50 percent more than "cheap" greenhouse glass. However, of equal or greater significance is the cost of the edge detail, and it is here that the size of ETFE cushions creates a great advantage over glazing systems. A typical glass panel of 1 x 4 meters has 10 meters of perimeter detail, or an area to edge ratio of 1:2.5. A typical ETFE cushion of 3 x 6 meters has a much more cost effective area to edge ratio of 1:1 or less for larger cushions.

Installation

To clamp cushion edges and attach cushions to the primary structure, fabricators use a range of proprietary aluminium extrusions. The extrusions incorporate thermal breaks, insulation and internal channels to provide a secondary backup system of drainage. Site installation is carried out by specially trained crews. After the edge extrusions are fixed to the primary structure, the plenum and inflation system are installed and purged to ensure that no debris is blown into the cushions. Plenum systems



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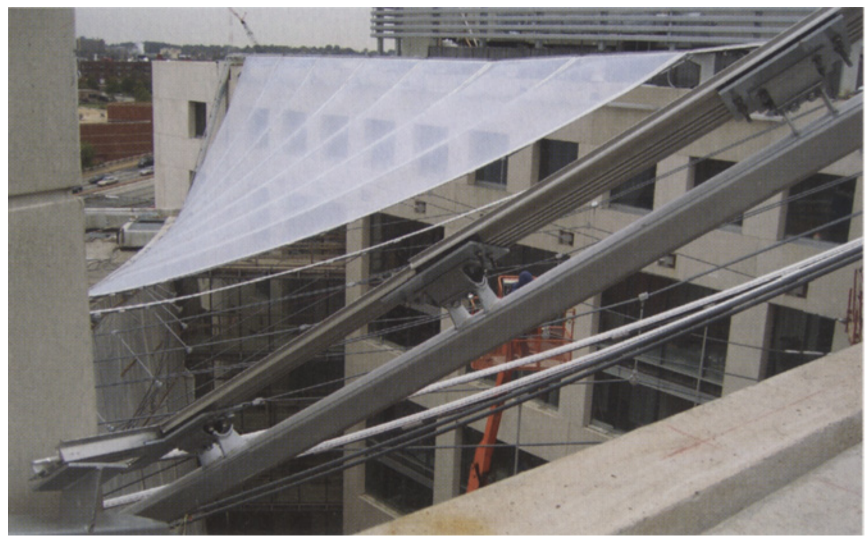

16__The most common cushion edge is a keder detail formed by a rope welded into the foil.

17–19

typically consist of a ring main or radial system with smaller diameter individual spurs to each cushion. Folded cushions are hoisted into place with ropes, unfurled and secured to the edge extrusions. The preinstalled valves are linked via flexible feeds to the plenums and the cushions are inflated to design pressure as soon as possible to stabilize the envelope. The inflated cushion surface is so smooth that it prevents most birds from gaining a footing. To keep birds off the perimeter extrusions, wires may be added, which are held by V-shaped aluminium brackets.

Inflation units comprise two backward airfoil blowers powered by electric motors. If the air supply fails, the building remains intact, with the principal impact being a temporary reduction of insulation values until air supply can be reinstated. Non-return valves in the inflation system ensure that an ETFE cushion will maintain pressure for 4–8 hours with no air supply. If power failure extends beyond this period of time, a backup generator or an uninterrupted power supply is recommended to prevent slack cushions from being buffeted and damaged by wind. ETFE cushions are considered to be airtight. When cushions are inflated, the system is kept topped up by a small inflation unit that compensates for seepage at joints and seams. Within the sealed cushions, which operate effectively as closed systems, there is only air pressure and little or no circulation of air. Although ETFE is airtight, it is vapor permeable, so dehumidifiers may need to be incorporated, particularly in buildings with high internal humidity, to suck out any moisture that seeps into the system.

Aspects of sustainability

In contrast with the earlier generation of air-supported structures, which required significant life-long energy input to maintain structural stability, cushion systems are energy efficient because the blowers are merely maintaining pressure, not creating air flow. A single inflation unit, which can service 1000 square meters of cushions by operating 50 percent of the time on average, uses a similar amount of power as an ordinary domestic light bulb. ETFE also scores well in life-cycle costing by being a low-maintenance material. Unlike fabrics, which are made of filaments that produce an uneven surface that can hold dirt and harbor mold, the smooth and non-stick surface of ETFE is self-cleaned externally by rain. The inner surface

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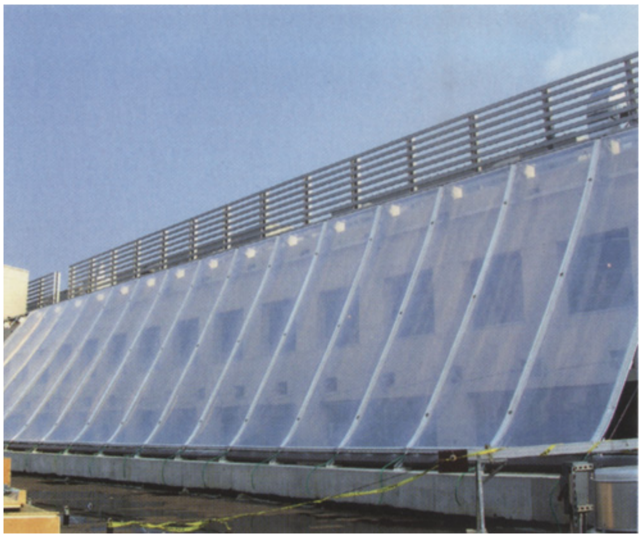

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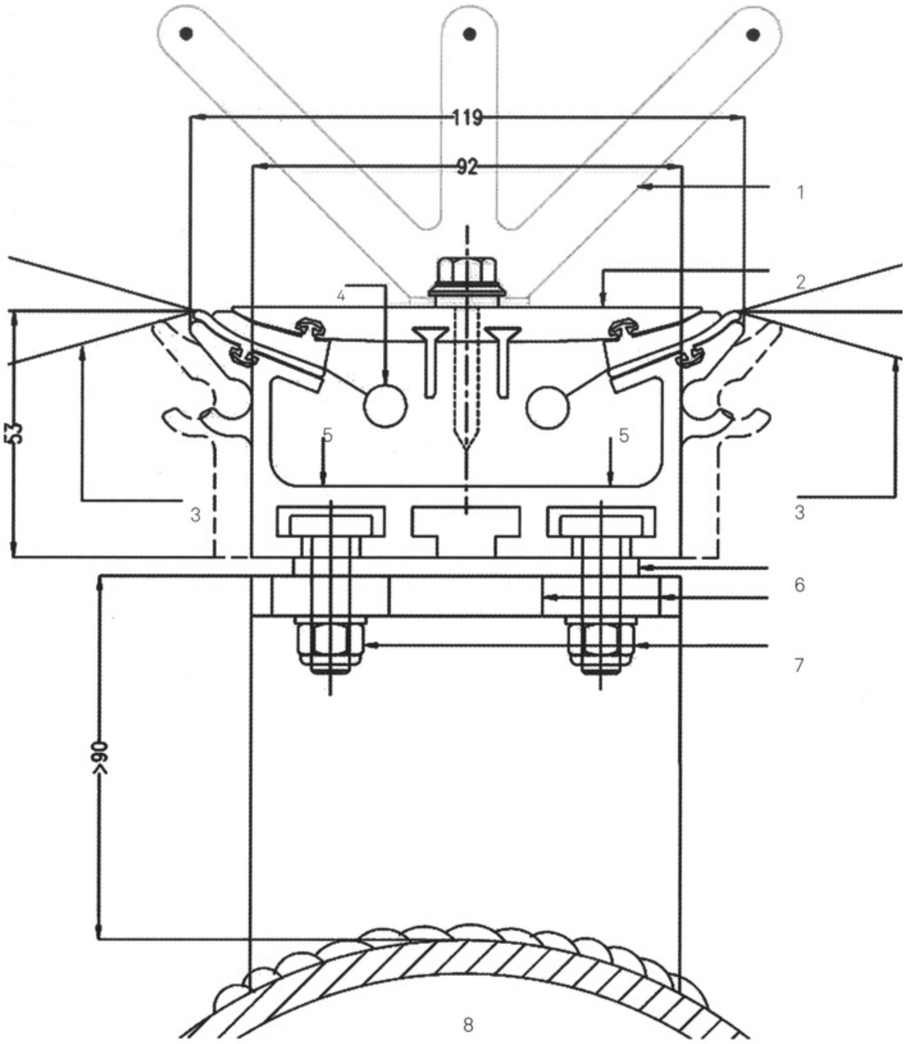
17–21__On site, cushions are unfolded, secured to proprietary aluminium extrusions, connected to the plenum system and inflated to prevent damage caused by wrinkles and wind. /
22__ETFE roof from below /
23__Inflated cushions fixed to a cable structure easily deform to define the desired warped surface. /



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24__Typical double-sided extrusion
1 bird deterrent wires on stainless steel carrier
2 extruded alloy cap with foamed EPDM gaskets
3 three layer ETFE cushion
4 keder cushion restraint
5 secondary drainage channel
6 foamed EPDM bimetallic separation
7 T-bar galvanized fixing bolts
8 support structure /

of cushions may be cleaned with water at approximately 5–10 year intervals, although in practice internal cleaning is rarely carried out because it simply does not seem to be necessary.

Chlorodifluouromethane, the raw material of ETFE, is not a petrochemical derivative and is admitted under the Montreal Protocol, which was implemented in 1989 to phase out substances that deplete the ozone layer. ETFE is an inert fluoropolymer that contains no leachable additives. The resin production process, which requires much less energy than glass production, is water-based and does not use solvents. With a mass of less than 1 kilogram per square meter, the light weight of ETFE yields further environmental advantages. Like NASA's satellites, very large foil cushions can be compacted for economic transport and inflated only once installed on site. Therefore, the embodied energy in the manufacture and transportation of ETFE is less than 1 percent of glass.

ETFE fits well into the technical nutrient category of materials, satisfying the cradle to cradle strategy for sustainability.[4] Although it is neither natural nor biodegradable, ETFE is 100 percent recyclable. Vector Foiltec, the leading company in architectural applications of ETFE, currently recycles all of the waste from the production process and is also a net importer of ETFE waste from other industries. While virgin ETFE foils must be used for cushions, other components of the system such as air valves and hoses are readily made from the recycled material. In addition to the sustainable attributes of the material itself, ETFE cushion envelopes contribute significantly to the environmental performance of the buildings in which they are used.

1__ John Schiers, editor. *Modern Fluoropolymers* (Chichester: John Wiley + Sons Ltd.) 1997, p.301.
2__ Id. at p. 307.
3__ Craig Schwitter. "Use of ETFE foils in lightweight roof constructions," *Proceedings of the IASS-ASCE International Symposium 1994 on Spatial, Lattice and Tension Structures* (Reston, Virginia: ASCE Publications) 1994, p. 624.
4__ For discussion of natural and technical nutrients, refer to *Cradle to Cradle* by William McDonough and Michael Braungart (New York: North Point Press) 2002.

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Pool Elypso, Deggendorf
PGF Planungsgesellschaft; Gollwitzer Architekten, 2003 /
25–27__Enclosed leisure pools have provided an enduring market for ETFE cushion systems. /

Stefan Lehnert

Risk and Reliability

For a new technology to successfully reach a market, especially a conservative market segment like the building industry, it has to have a profound foundation based on sound reasoning. The philosophical and visionary foundations for ETFE cladding technology were well laid by Buckminster Fuller, Frei Otto, Ted Happold and Ian Liddell, among others. During the past three decades, the translation from vision to reality, and from experimental projects to broad acceptance and application in the industry have required risk-taking and innovation.

For ETFE cladding technology to survive and grow, it had – and still has – to pass the often severe demands of the reality test. Instead of trying to adapt ETFE technology to conform to a regulatory framework designed for more conventional materials, questions about watertightness, life safety, fire codes, structural integrity of ETFE systems over expected life span, material and system longevity and serviceability, and even building insurance have had to be addressed from first principles in order to make the technology acceptable to investors and architects within an industry that is rightly focused on the production of safe and durable buildings.

A few examples help to tell the tale of issues that had to be tackled during the evolution of ETFE technology. When ETFE foil cladding systems were initially used in the early 1980s, one obstacle was that there was no welding equipment available on the market that could function on an industrial level. Fluoropolymers require special production and welding equipment for various reasons. Their melting point is three times higher than PVC materials or similar low performance plastics. In addition, when heated to the melting point, fluoropolymers become highly corrosive. As a consequence, all machinery must be protected from direct contact with hot ETFE to avoid corrosion of machine parts and to ensure reliable quality in performance over time. Therefore, our first step towards making ETFE cladding systems feasible was the development of welding equipment with a precise temperature control mechanism that could produce consistently high quality welds for ETFE foil. Even now, only limited aspects of this welding technology have penetrated the industry. The most reliable and productive equipment is still not available to the general market but remains proprietary and specific to Vector Foiltec.

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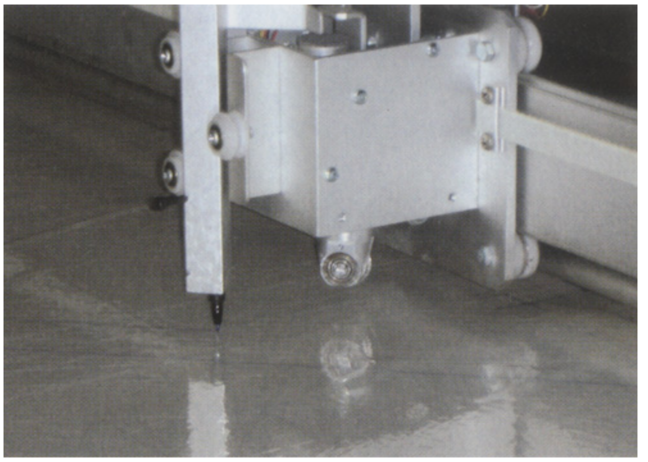

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1__A digital x-y plotter with a suction table, 4 x 12 m in size, is directly linked to the Vector Foiltec design office. /
2__Tool carrier of plotter, equipped with pen /

Very early architectural trial applications of ETFE in the 1970s, conducted by various universities, treated foils in the same way as fabrics or PVC, not taking into account the fact that foils are a lot weaker, more slippery and more vulnerable to the environment than fabrics. Likewise, fabrics do not offer significant environmental benefits, apart from rain and sun protection. New strategies, both conceptual and technical, had to be developed to cope with the material character of ETFE and to exploit the advantages stemming from the ability of ETFE systems to act as climatic envelopes.

When working with ETFE, it is important that designers put aside assumptions gained from experience in working with other materials. A recent example of the danger of handling ETFE like other materials is provided by the Allianz Arena, where cushion drainage details, similar to those used for air-supported fabric stadium roofs in the 1970s, have not been able to successfully deal with heavy snow loads. Problem solving with ETFE is often counter-intuitive. Contrary to principles used on other kinds of roofs, for example, instead of increasing cushion camber, or slope, to shed water, flatter cushions minimize the risk of ponding.

Probably the biggest step contributing to the eventual success of ETFE systems has been the progress made in the engineering of the material itself as well as the engineering of supporting structures. When materials fail, it is often because they are not strong enough. With other materials, greater strength generally requires greater thickness. Using ETFE, very often the opposite is the case. If ETFE components fail, there is a high probability that they have been over-designed. Foils that are too thick become brittle and develop a tendency to fail, even though from an engineering standpoint stress numbers are within the allowable range.

ETFE is a highly elastic material and also allows plastic deformation up to certain limits. In fact, allowance for plastic deformation of ETFE foil is now, in many instances, designed into the geometry of the enclosure system. In such cases, plastic deformation takes a certain amount of time, and the final shape of ETFE envelopes is only achieved some two or three years after the building has been completed. In an industry more attuned to the certainty of form-giving than to the risk of long-term form-finding, many discussions and much convincing has been

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3__Every foil strip is cut to its final geometry and size. /
4__Foils awaiting processing at welding machine. Automatic storage machine in the background /

required over the years to gain acceptance for this engineering approach.

ETFE engineering, if done well, takes advantage of both the elasticity and plasticity of the material, allowing it to give and to move. The big advantage of pneumatic cushion technology in conjunction with ETFE is that the elongation of the material actually initiates a load reduction cycle. Due to the shape change of the cushion, loads in the structural system do not increase as much as increases in applied loads would suggest. Single layer ETFE enclosure systems cannot take advantage of this feature. Such systems can only be stressed up to a limit, in order to guarantee that the foils do not creep or plastically deform under given design loads. Above this limit, ETFE foils in single layer systems become slack and flap in the wind.

In contrast, because ETFE cushions are forgiving, both the cushions and their supporting structures can flex to a very high degree. Movement, whether due to loads or temperature changes, can be dealt with basically without limits. This characteristic, if applied intelligently, allows lightweight and wide span structures to be designed which previously had been unrealistic. In particular, biaxial and uniaxial cable structures, which are extremely cost effective for long spans, work very well with enclosures of ETFE cushion systems.

Another area in which ETFE systems have enabled new approaches to engineering is environmental and energy efficient climate design. While traditional building products offer the designer a specific appearance and related performance in terms of U-values, multi layer ETFE systems allow the designer to specify U-values, transparency requirements and reflectivity features, as well as to customize the visual appearance of the cladding system. With standard products, the engineer feeds product-specific numbers into computer algorithms to define heating and cooling capacity. With ETFE systems, the designer can specify the performance to be achieved. The build up of the ETFE system is then developed based on the requirements of the design.

Although relatively new in the arena of architectural materials and assemblies, ETFE cushion systems are proving to be extremely safe due to the light weight and unexpected strength of ETFE combined with its high elasticity. Some 25 years ago, only non-combustible materials

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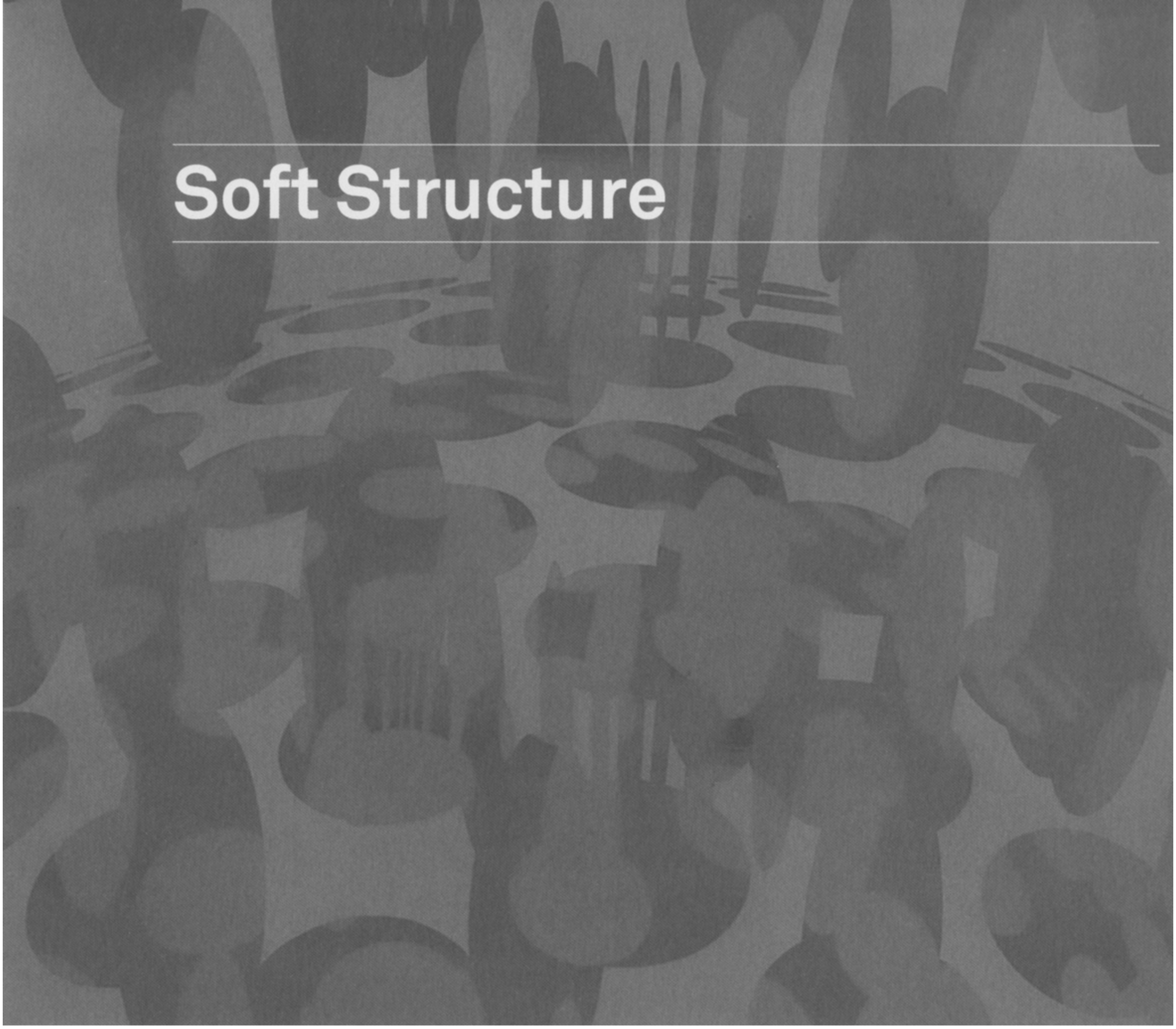
5___State of the art welding equipment /
6___Cushion manufacturing requires a skilled and well-trained labor force. /

were considered safe in buildings, and it was virtually impossible to use any type of plastic because of problems with combustibility and structural weakness. ETFE's behavior in fires turns these previous assumptions about plastic on their heads. Fire performance and many other attributes of ETFE are widely accepted today by approval bodies around the world, and we are actually seeing – for good reason – the first building approvals that insist on the use of ETFE foils because of the benefits they offer in life safety issues. In addition, ETFE is proving to have a much longer lifespan than fabrics or plastic films used in architectural applications.

Over the years we have been able to alter many of the preconceptions linked with plastics and their application within the building industry. Now widely accepted within the architectural community, ETFE cushion technology looks deceptively simple but remains highly complex and specialized. Clients should take care in seeking suppliers with a strong architectural and engineering background who will take responsibility from design concept through detailing, fabrication, site assembly and long-term maintenance. It has taken the team at Vector Foiltec over 25 years of research and development of materials, production procedures, design concepts, structural engineering, environmental servicing strategies and health and safety features to arrive at a position where the firm is able to offer a product that adds a totally new facet to the character of today's sustainable architecture. In recent years, we have seen some extraordinary and impressive structures with ETFE cushion envelope systems. This book presents only a small excerpt from an array of projects that could not have been built with any other technology.

Soft Structure

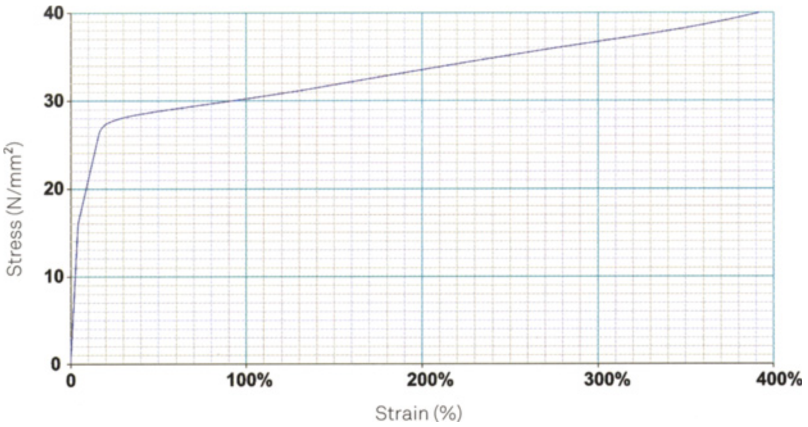


During the eighties, architects and engineers turned away from inflatable buildings and began to explore composite systems that, as defined earlier by Frei Otto, combine inflated cushions with supporting structures. In these composite systems, instead of air playing the primary structural role, its purposes are to prestress the membrane to prevent it from going slack and to enhance the insulation performance of the building envelope. Cushion systems and ETFE have proved to be highly compatible.

Active homeostasis

Structurally, ETFE is a soft technology, both with regard to the properties of the material itself and its behavior in cushion enclosure systems. Unlike many building materials, which tend to be deployed in ways that maximize their strengths, the advantages of ETFE lie in its ductility. Compared to materials like steel, concrete and glass, ETFE starts to yield at a very low level of stress, approximately 23.5 N/mm^2 or 2.3 percent strain. What might be considered a liability is transformed into an asset by the fact that this material can elongate up to 400 percent before failing. ETFE is therefore well suited to cushion systems that are prestressed by internal air pressure, which ensures that the membrane remains in tension and therefore stable. These systems are typically inflated to a low pressure ranging from 200–600 Pa, approximately 0.2–0.6 percent of the air pressure of an automobile tire, which is sufficient to maintain tension in excess of normal external forces, including wind and snow. Normal prestress pressures in the cushions coupled with external live loads push the ETFE membrane close to the yield point of the material.[1] Although the foils are very thin and lightweight, the high loadbearing capacity of ETFE and its ability to elongate without failing mean that ETFE cushion systems are significantly stronger than conventional structure and enclosure systems, whether made of timber, steel, aluminium or other building materials.

In 1968, Reyner Banham described the performance of pneumatic structures by comparing them to more familiar forms of architecture: "All architecture has to mediate between an outer and an inner environment in some way, but if you can sense a rigid structure actually doing it (dripping sounds, tiles flying off, windows rattling) it usually means a malfunction. An inflatable, on the other hand, in



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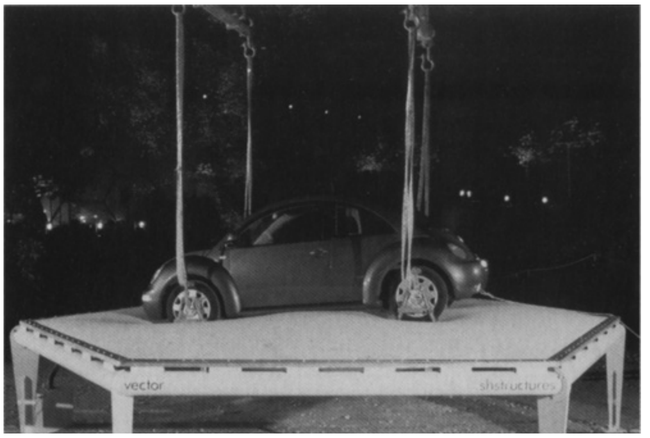

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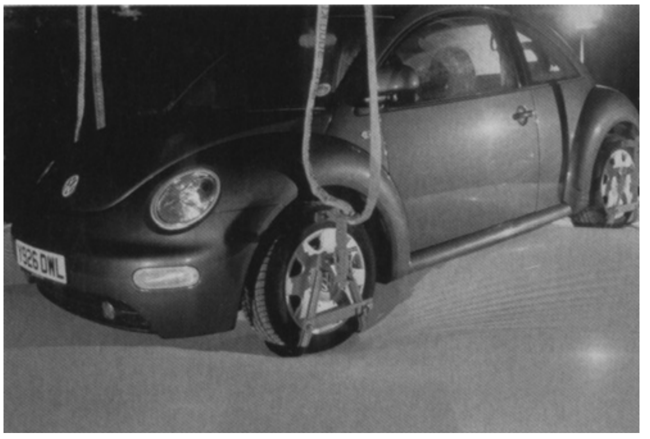

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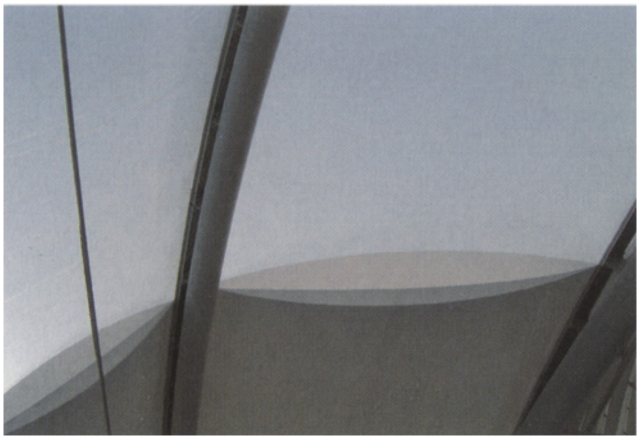
1__Stress/strain diagram /
2–3__The high loadbearing capacity of ETFE cushions was demonstrated on the UK television program, Tomorrow's World. /

its state of active homeostasis, trimming, adjusting and taking up strains, is malfunctioning if it doesn't squirm or creak. As an adjustable and largely self-regulating membrane it is more truly like the skin of a living creature than the metaphorical 'skin' of, say, a glass-walled office block."

Reflecting upon his experimental occupation of a small inflated plastic dome, he added, "The beauty of that simple wind-bag was the directness and continuity of its response. Every slight change of state inside or out – even a heated conversation – brought compensating movement in the skin, not through the expensive intervention of a computer, but by direct variation of curvature under balance of pressures. For the human occupant it was a kind of partnership relation with the enclosing membrane, each going independently but sympathetically about its business."[2]

Although Banham was referring specifically to air-supported inflatables, his characterization of an actively responding, self-regulating membrane is also appropriate for cushion structures. When inflated, ETFE cushions reach a form that is determined by the equilibrium of internal pressure with surface tensions and radii of curvature. Instead of relying on stiffness, cushions respond to dynamic, differential loads by deformation, which absorbs energy and slows movement. Unlike the ETFE foil itself, cushions can recover their shape. The softness of ETFE and the cushion system are interactive. If the cushion is too heavily loaded, the foil yields, then hardens and becomes stronger. This elongation produces areas of more pronounced curvature, which in turn reduce stress. The weakness of the material and the deformation of cushions under loading therefore work together to create a self-compensating system that tends toward equilibrium.

Inflated ETFE cushions weigh approximately 1 percent of conventional enclosure systems with comparable performance, lightening the dead loads to be carried by the primary structure. Compared to a rule-of-thumb maximum span for glass of 1.5 meters, one-way ETFE cushions can span 3–5 meters and two-way systems up to 11 meters, depending on the loads. Consequently, with cladding modules large enough to be coordinated with primary structure, ETFE systems typically eliminate the need for secondary structure. The size of primary structural members, in addition to being determined by span and loading, is also a function of the allowable movement and deflection of



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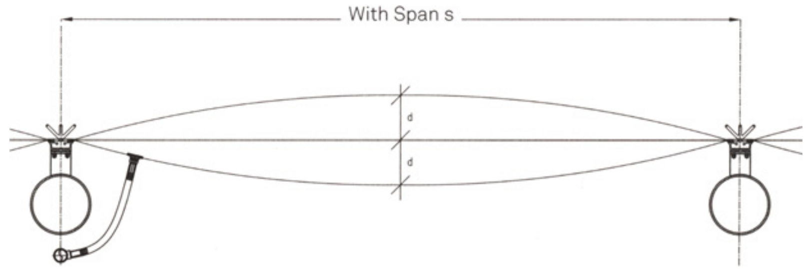

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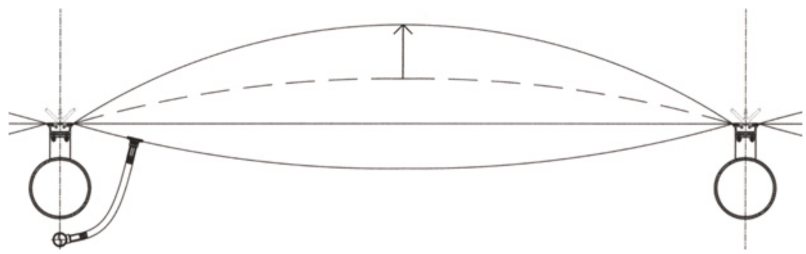

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4__Cushion camber contributes to the appearance and performance of the building envelope. /
5__Cushion section and camber /
6__ETFE's weakness and the deformation of cushions under loading work together to create a self-compensating system. The increase in camber results in decrease in stress. /

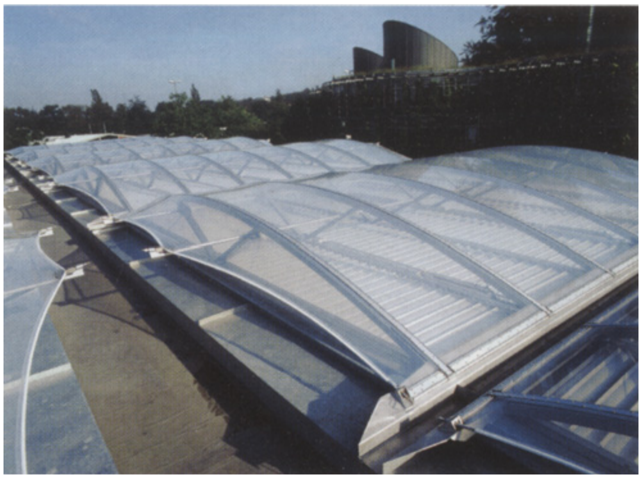
the building's cladding system. Because ETFE cushions can deflect and deform considerably without adverse structural consequences, and because they absorb movement through deformation, primary structural members are further lightened by not being required to be rigid.

Form, climate and weather

Synclastic form, which is characterized by having the same direction of curvature at all section cuts, is most efficient as a sphere, which – like a bubble or a balloon – has maximum volume and minimum surface area. To pull an inflated balloon into a cushion is a difficult task. Since the cushion desires to be a sphere, the tighter the radius of curvature of the cushion surface, the lower the material stress. Although flatter cushions with greater radii of curvature are subject to higher material stresses, they use less material and are not subjected to secondary wind loads such as windward and leeward effects, which can induce flutter in the membrane. Furthermore, a key consideration is to prevent water ponding in the event of cushion deflation. The flatter the cushion, the less risk of ponding for any roof orientation. Therefore, the design strategy for cushions for any given size and load combination, is to pattern the cushion to have the least rise for the designated material thickness. Typically, the optimum camber from the neutral axis of the cushion ranges from 6–20 percent of span.

Like most materials, ETFE expands and contracts in response to changes of temperature. However, its range of elasticity is very limited. As might be inferred from its yield characteristics, ETFE creeps at stresses as low as 10–12 N/mm^2. If a membrane is held under tension, the stress in the membrane is dependent on temperature. In response to seasonal temperature changes, if the stress induced in an ETFE membrane exceeds the creep stress, the membrane will yield, relax, become floppy and fail. For this reason, tensioned anticlastic forms do not work well using ETFE unless they are very small in scale. In contrast, the self-compensating equilibrium of air pressure in cushioned synclastic structures accommodates the effects of creep.

ETFE suffers some loss of strength at temperatures of 70 degrees Celsius and higher. Its use in extremely hot climates must therefore be carefully controlled. If temperature were considered in isolation, large cushions would be used in temperate and cold zones, and smaller ones



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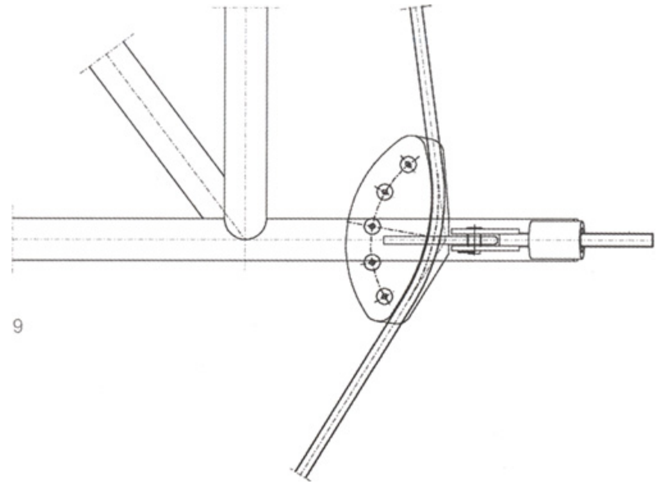

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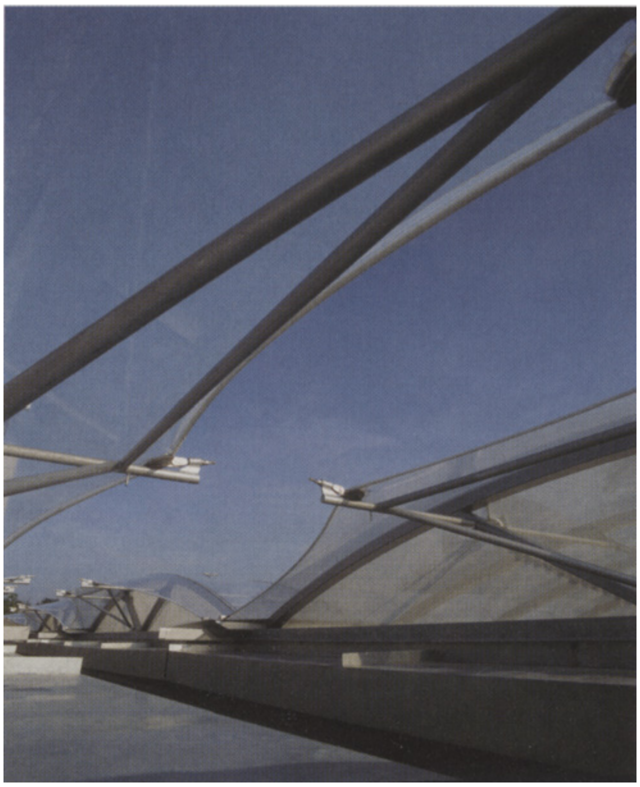

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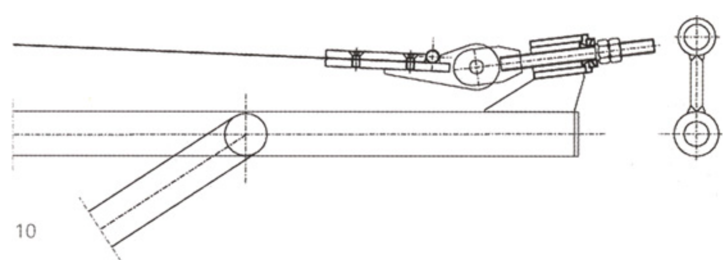

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DBU Conference and Exhibition Building, Osnabrück
Herzog + Partner, 2002 /
7__A single layer canopy above a weatherproof glazed roof and shade louvers demonstrates ETFE's successful use for small-scale tensioned anticlastic forms. /
8–10__A cable seamed into the scalloped edge tensions the ETFE membrane. /

would be deemed more suitable for warm regions. However, temperature is rarely the critical determinant of cushion shape and size. Due to the very large area-to-volume ratio of thin films, the foils are cooled by wind so that their surface temperatures are close to ambient temperature whenever the wind is blowing. Thus, the foils cool, becoming stronger at precisely the time that the envelope requires their maximum load-carrying ability.

In very cold climates, snow loads may become a significant factor. ETFE cushions for roofs have been constructed to handle snow loads of 3000 kilograms per square meter, equivalent to approximately 3 meters of snow. Where very heavy loads are anticipated, reinforcement in the form of cable nets can be introduced under the cushions to provide additional support. Alternatively, air pressure in the cushions may be temporarily increased.

In practice, wind loads are almost always the primary factor governing cushion shape and maximum size, with systems capable of being designed to handle wind suction loads of over 5kN (500 kilograms) per square meter. The large panel area of lightweight ETFE components and the ability of both the material and the cushion to deform under load produce significant advantages in designing for live loads, particularly wind. In general, codes are structured so that the larger the area of the cladding component, the lower the wind load per square meter. The rationale is that high pressures are associated with short term localized gusts, and the cushions act to spread the load over space and time, like diluting the force of a hurricane over a large geographic area for a full year. ETFE cushion systems damp wind loads by absorbing wind energy and can therefore be designed for lower wind loads per square meter than comparable rigid building envelopes, which typically have smaller modules.

This philosophy of damping extends even to the detailing. Unlike a glazed curtain wall assembly, where every mullion must accommodate movement arising from atmospheric pressure, temperature, weather and structure, ETFE cushions are detailed so that these movements are not concentrated at the edges but, like butter on toast, are absorbed across the entire pliable surface, reducing and often eliminating the need for conventional movement joints. Many building problems are indeed caused by failure of the junctions between materials where differential structural

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Piccadilly Station, Manchester
Building Design Partnership, 2002 /
11–13__The high impact resistance of ETFE cushions was demonstrated during construction, when a metal cladding panel that fell from several stories above did not damage the roof membrane. /

Hampshire Tennis and Health Club, Eastleigh
Euan Borland Architects, 1995 /
14–16__ETFE cushions combine with a mast-supported tensile structure to create a uniaxial cable net. /

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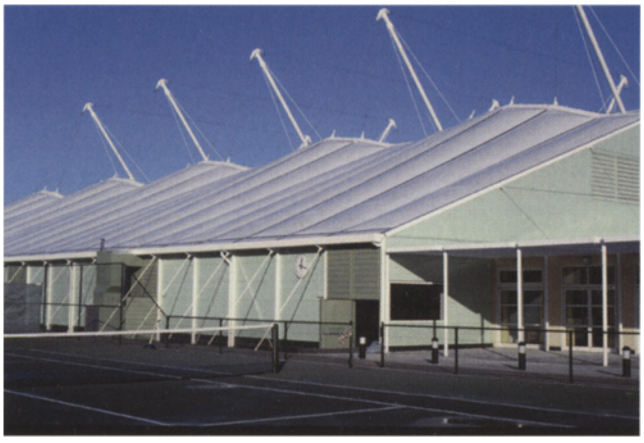
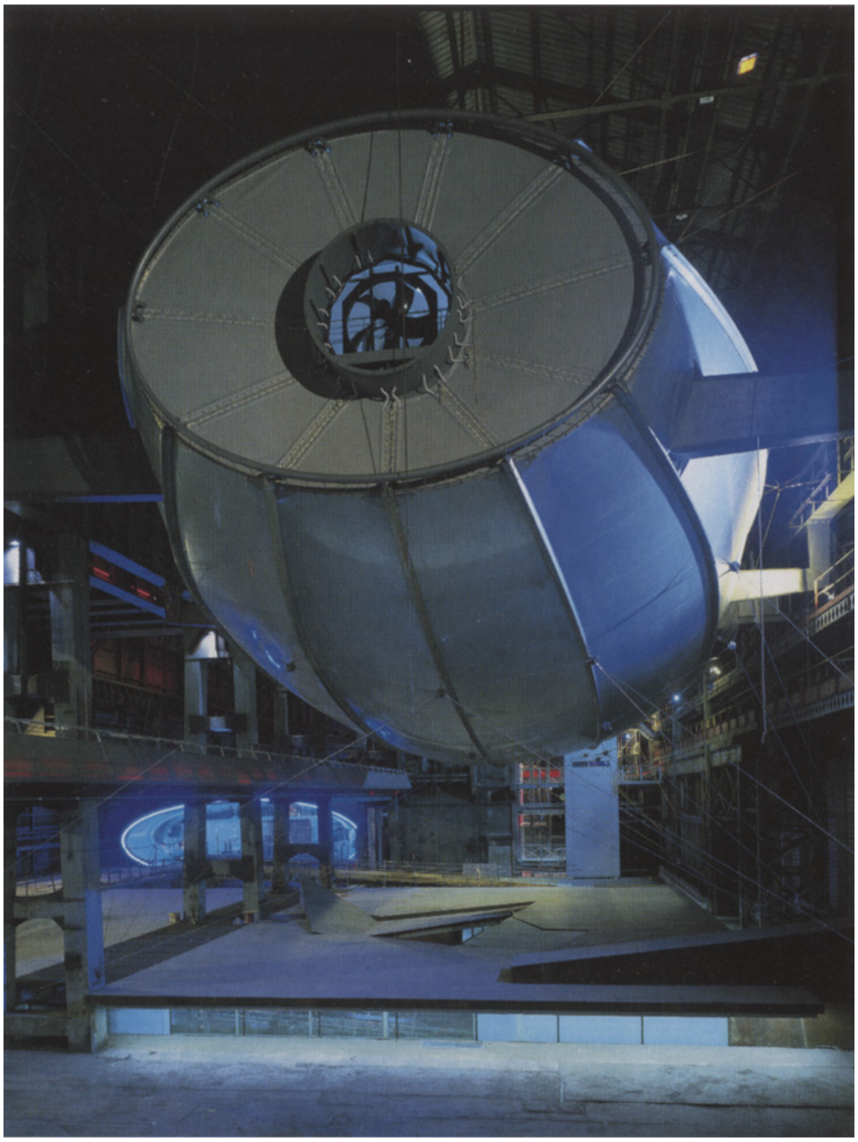



and thermal movements have to be accommodated. Although glass, for example, is a long-life material, modern glazing systems have a design life of only 15–20 years because gaskets and seals for double glazed units fail, diminishing thermal performance and allowing air and water penetration. In contrast, because ETFE is flexible and the cushions are much larger than conventional components, building movements are distributed, liberating the much reduced number of junctions from the requirement to accommodate building movement and vastly extending the design life of the envelope.

Strength and flexibility

Primary structures supporting ETFE cushions must be designed for the maximum combination of prestress and applied loads. Within a cushion system, perimeter loads between cushions are in equilibrium. However, at the perimeter of the system, for example at the edge of a roof, these forces must be absorbed by the primary structure. Cushion edges must be strong enough to transmit these loads into the perimeter structure and sufficiently flexible to deal with dynamic and differential loads from varying atmospheric pressure, wind, rain and snow. The most typical detail is a rope of polyester or PVC in an ETFE sleeve, which is continuously welded to the cushion perimeter and either clamped or slipped into an aluminium extrusion. The flexibility of ETFE is a function of its thinness, with a maximum recommended foil thickness for building applications of 250 microns. Thicker foils become brittle and can potentially crack. Therefore, another limiting factor on cushion size is material thickness and the requirement to transmit imposed loads to the cushion perimeter.

When prestressed by air pressure, ETFE foils become strong in tension and have high impact resistance. Although ETFE foil may be punctured by sharp objects, its high resistance to tear propagation means that a puncture will not develop into a large rupture. Furthermore, multi layer cushions are designed to seal automatically when damaged. If the outer layer is punctured, the middle layer of the cushion is sucked up to cover the hole internally. Each cushion operates autonomously, so damage tends to be contained locally. Minor damage can be easily repaired in situ with the equivalent of a puncture kit and typically does not entail replacement of cushions.



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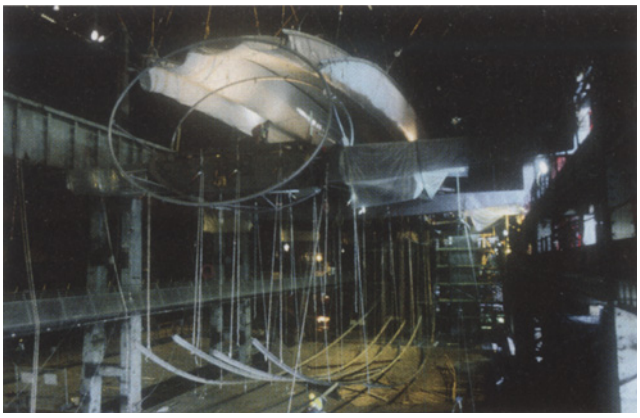
Air Pavilion, Magna Project, Rotherham
Wilkinson Eyre Architects, 2000 /
17__The pavilion seemingly floats in the cavernous space of the redundant steelworks. /

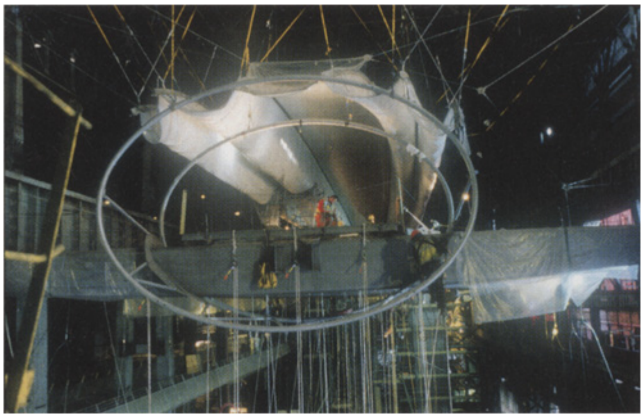
Structural innovation and ETFE

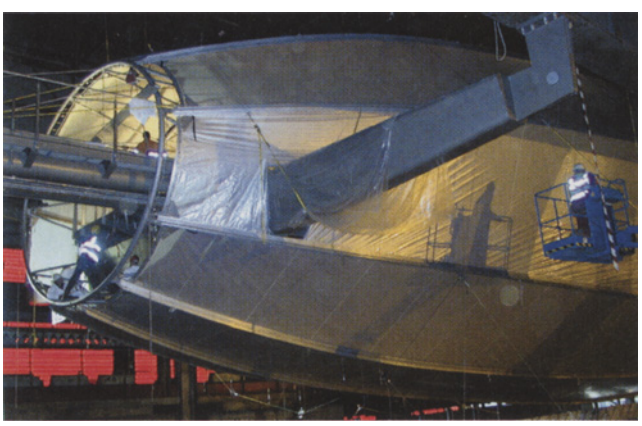
Compatible with both compressive and tensile structures, ETFE cushion systems have spawned a number of innovative structural strategies. The enclosure for the Hampshire Tennis and Health Club at Eastleigh, completed in 1995, is a composite system of ETFE cushions supported by a tensile primary structure, the first uniaxial cable net. This elegant minimalist envelope shelters ten tennis courts with an area of 6000 square meters. The structure comprises a ridge cable supported by opposed cable-stabilized steel masts on paired columns, which form a central spine in the two-bay enclosure. Prestressed cables extending from the ridge to perimeter ground anchors carry three layer translucent white ETFE cushions. The ETFE cushions, approximately 3 meters wide and 18 meters long, are clamped to the cable net so as to allow full movement in fluctuating wind and thermal conditions. As the only component connecting the parallel cables, the ETFE cushions work as a fluid damping diaphragm that stabilizes the entire structure. The pressure-tensioned membrane acts like a series of springs distributed across its surface at right angles to the cables. These springs stabilize the uniaxial net, allowing it to work as a fluid-damped biaxial system in which one axis is defined by cables and the other by air-pressurized foils.

The Air Pavilion at Magna, completed in 2000, takes this concept further, creating a symbiotic structure in which ETFE cushions and a cable net are structurally interdependent. Provocatively housed in a redundant steel reprocessing plant at Rotherham, this museum of steel focuses on the former industrial economy of the region and on the elements essential to steel manufacture – earth, fire, air and water. Each element is represented by a pavilion placed within one bay of the vast 400 meter long and 35 meter high industrial shell. The Air Pavilion, a zeppelin-shaped enclosure located in the roof zone, was originally conceived as a conventional steel frame clad with ETFE cushions. To meet the constraints of a tight budget, the frame was replaced with lightweight cable hoops, that are stressed by the inflated cushions.

The pavilion is 44 meters long with a diameter of 16.7 meters at the center that tapers to 5 meters at the ends. Two elliptical compression rings at each end, made of 114 millimeter diameter steel tubes, are joined by diagonal







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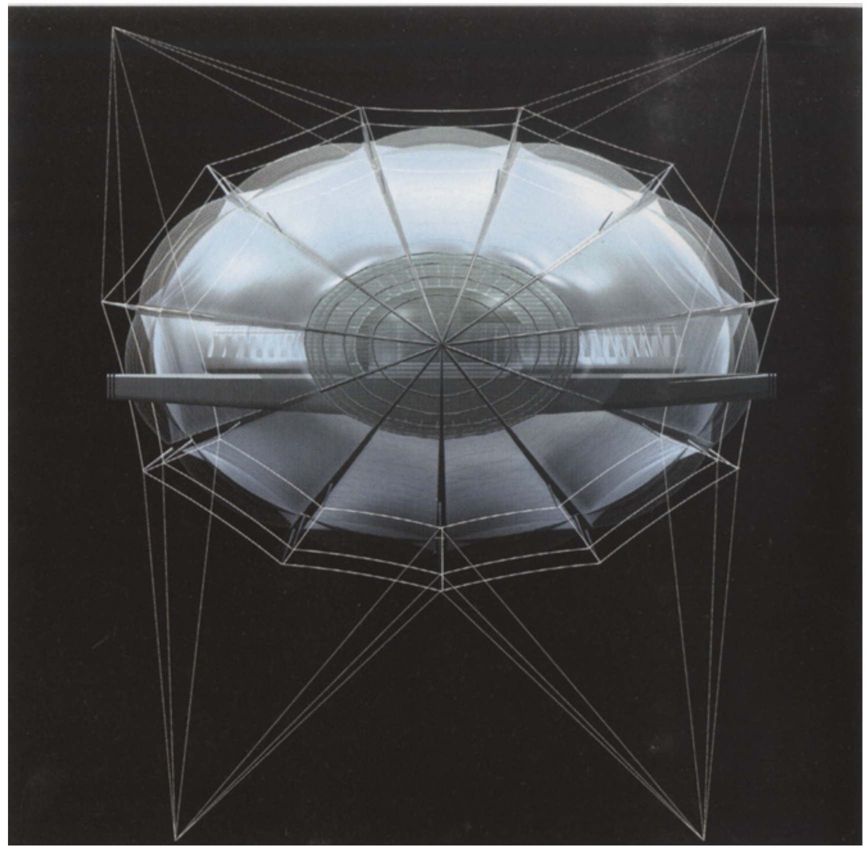

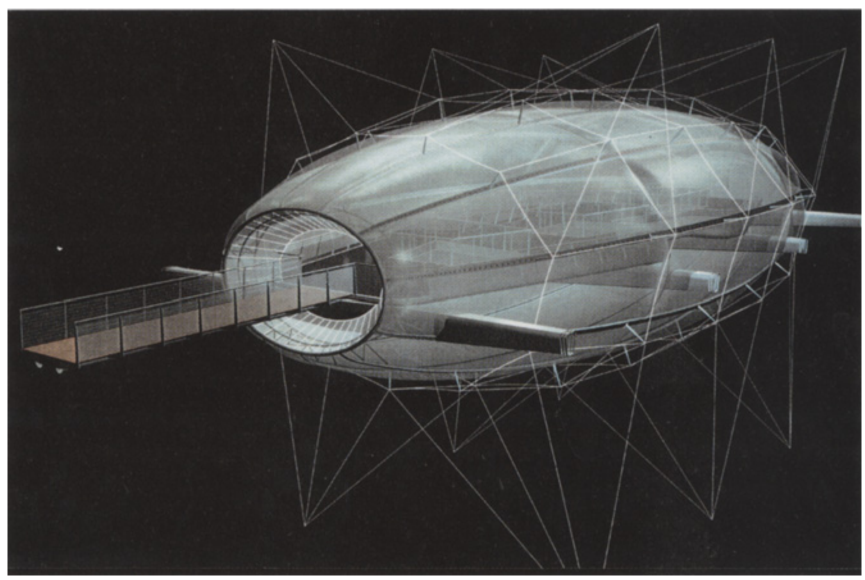

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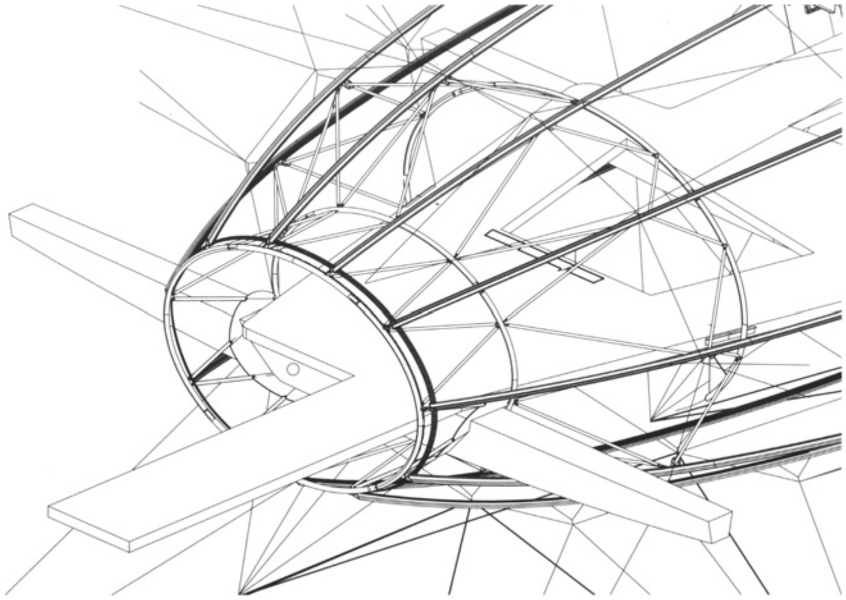
18–21__The Air Pavilion under construction /
22–23__A cable net is stressed by inflated ETFE cushions, creating a symbiotic structure. /



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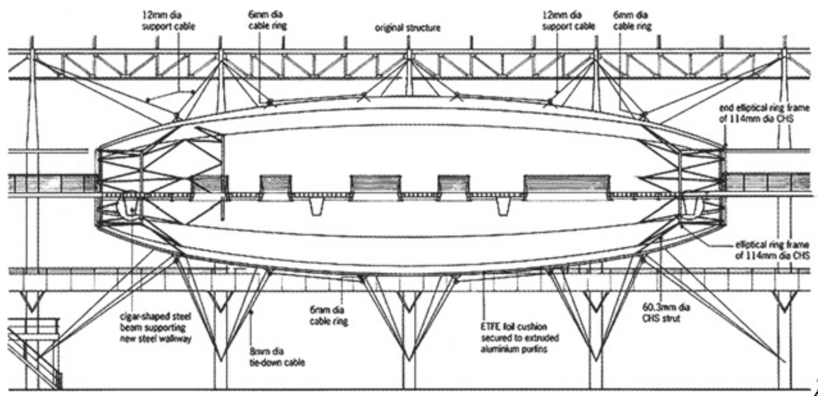

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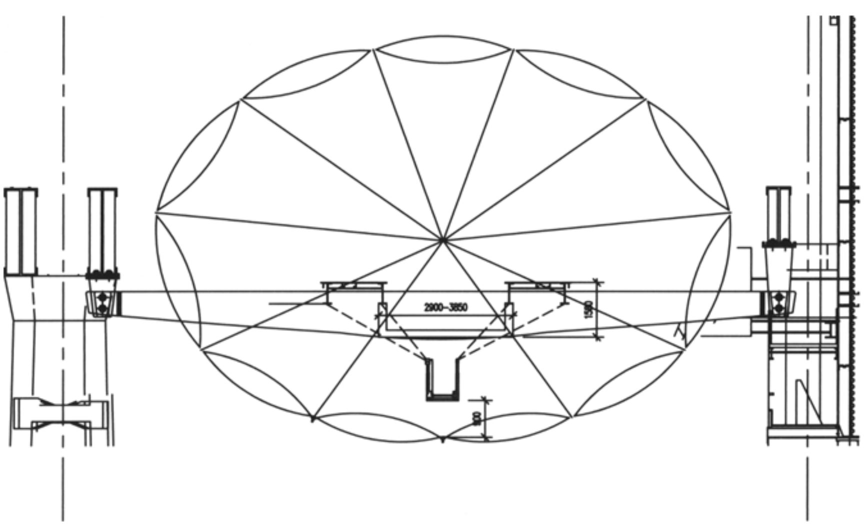

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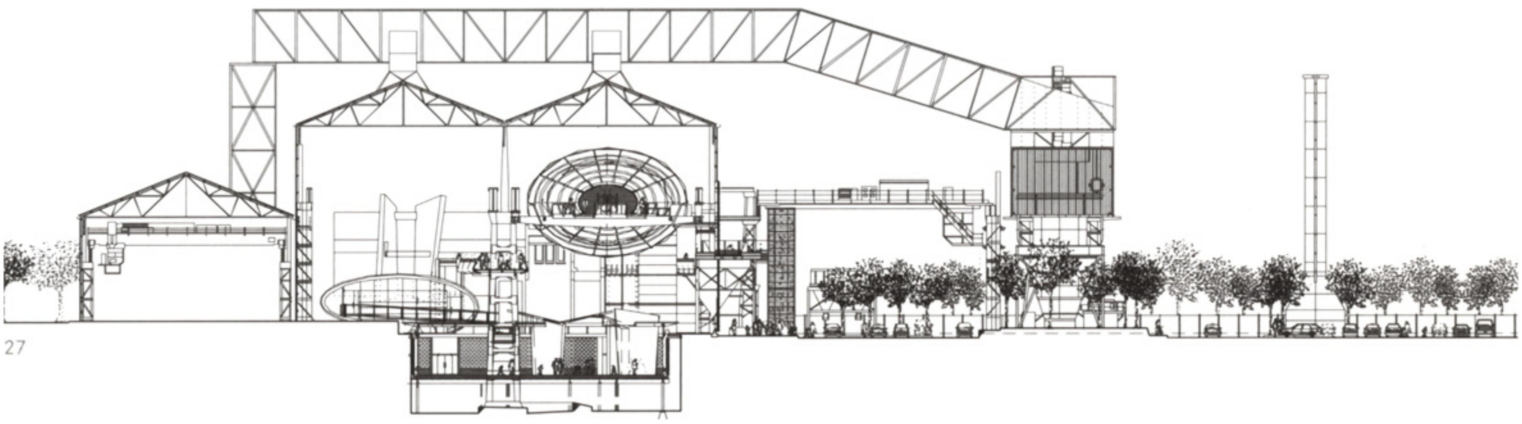
24__Interface of steel collars, cable net and observation deck /
25__Longitudinal section showing cable connections to existing structure /
26__Cross sectional diagram of pavillion's geometry /



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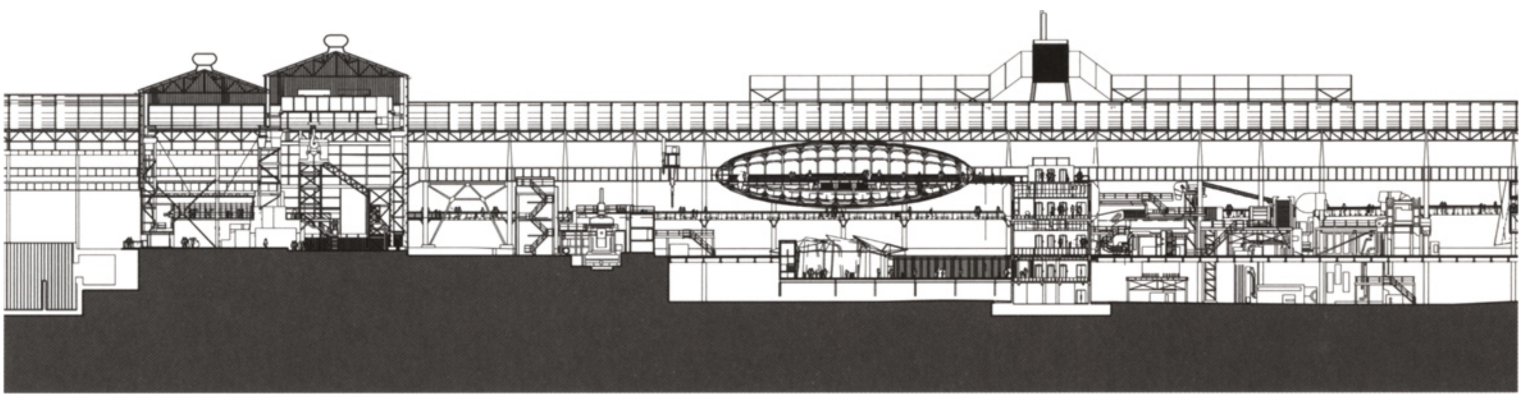

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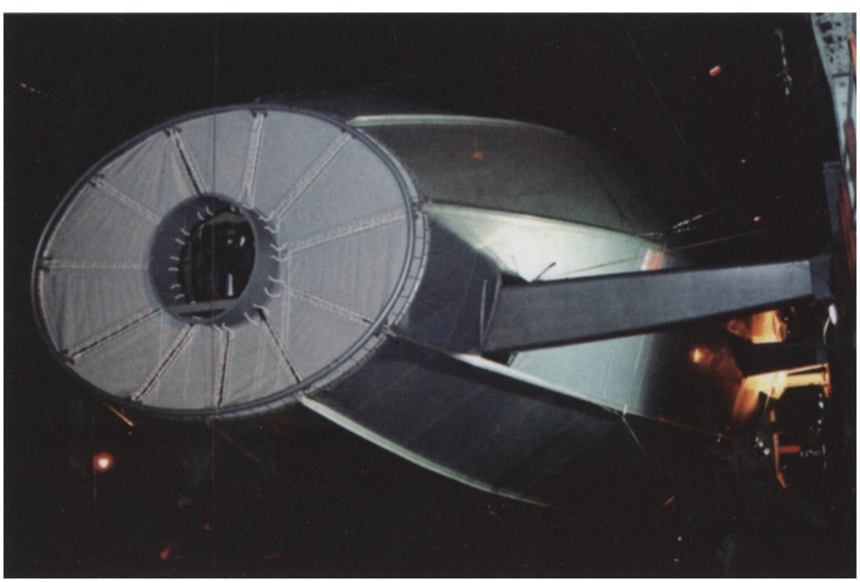

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27–28__Cross and longitudinal section showing position of Air Pavilion within the steel museum /
29__The Air Pavilion highlights the contrast between heavy industry and new, lightweight technologies. /

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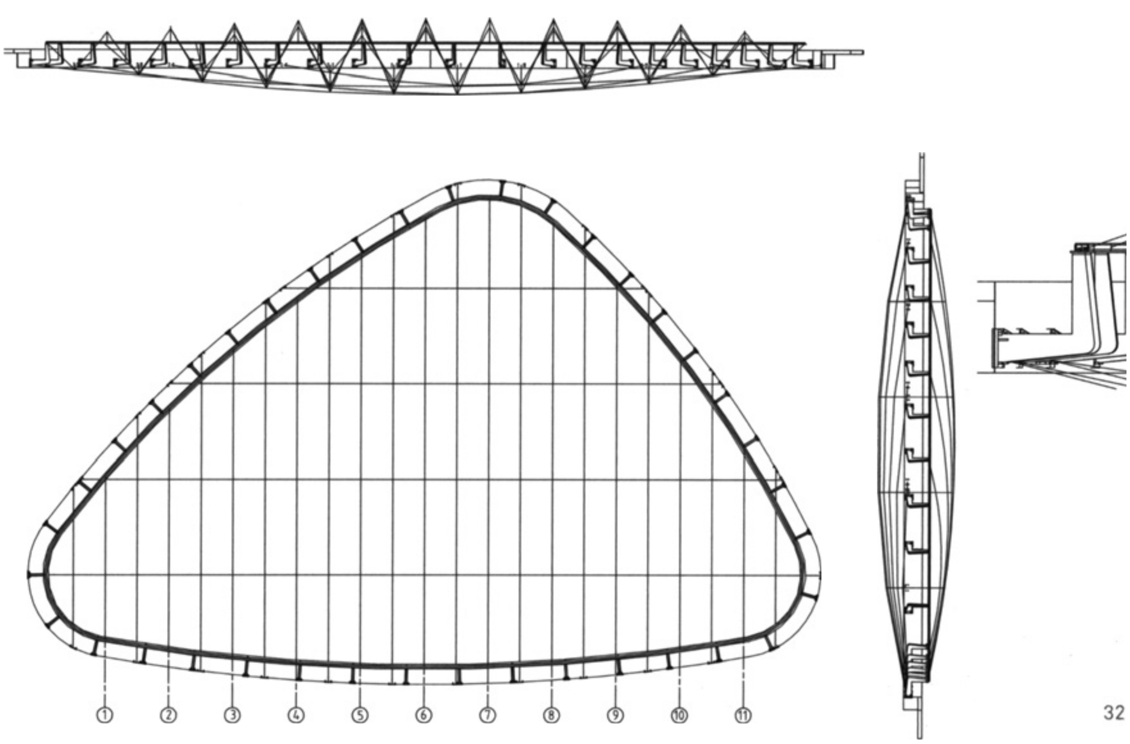

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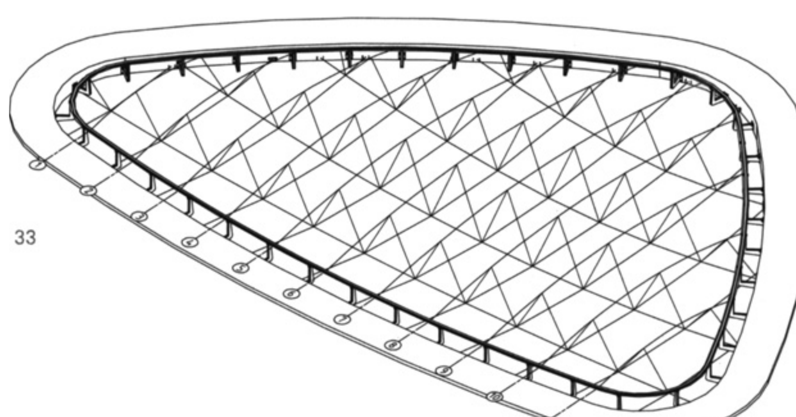

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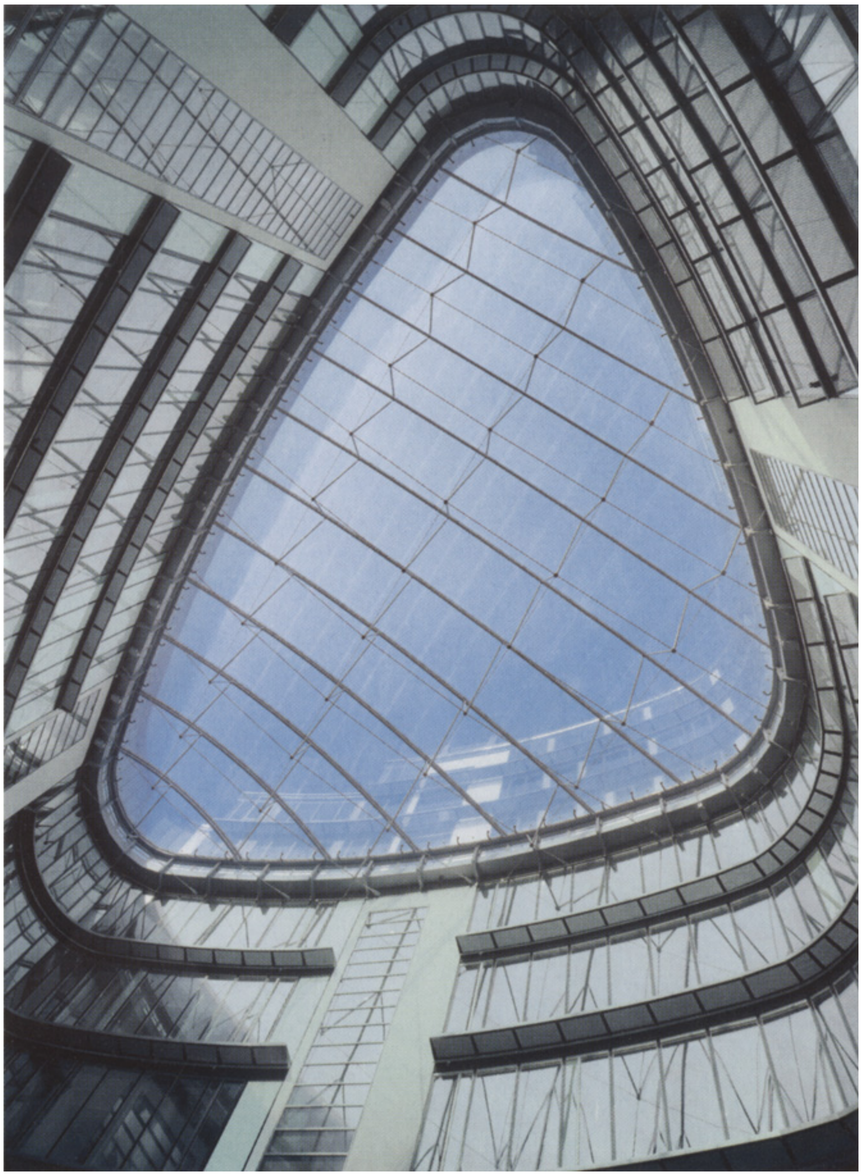
Oval at Baseler Platz, Frankfurt
AS&P – Albert Speer & Partner, 2004 /
30–31__The ETFE cushion roof of an amorphous atrium is supported by bowstring trusses that are stabilized by cables in two directions. /
32–33__Structural plan, sections and 3-D view /



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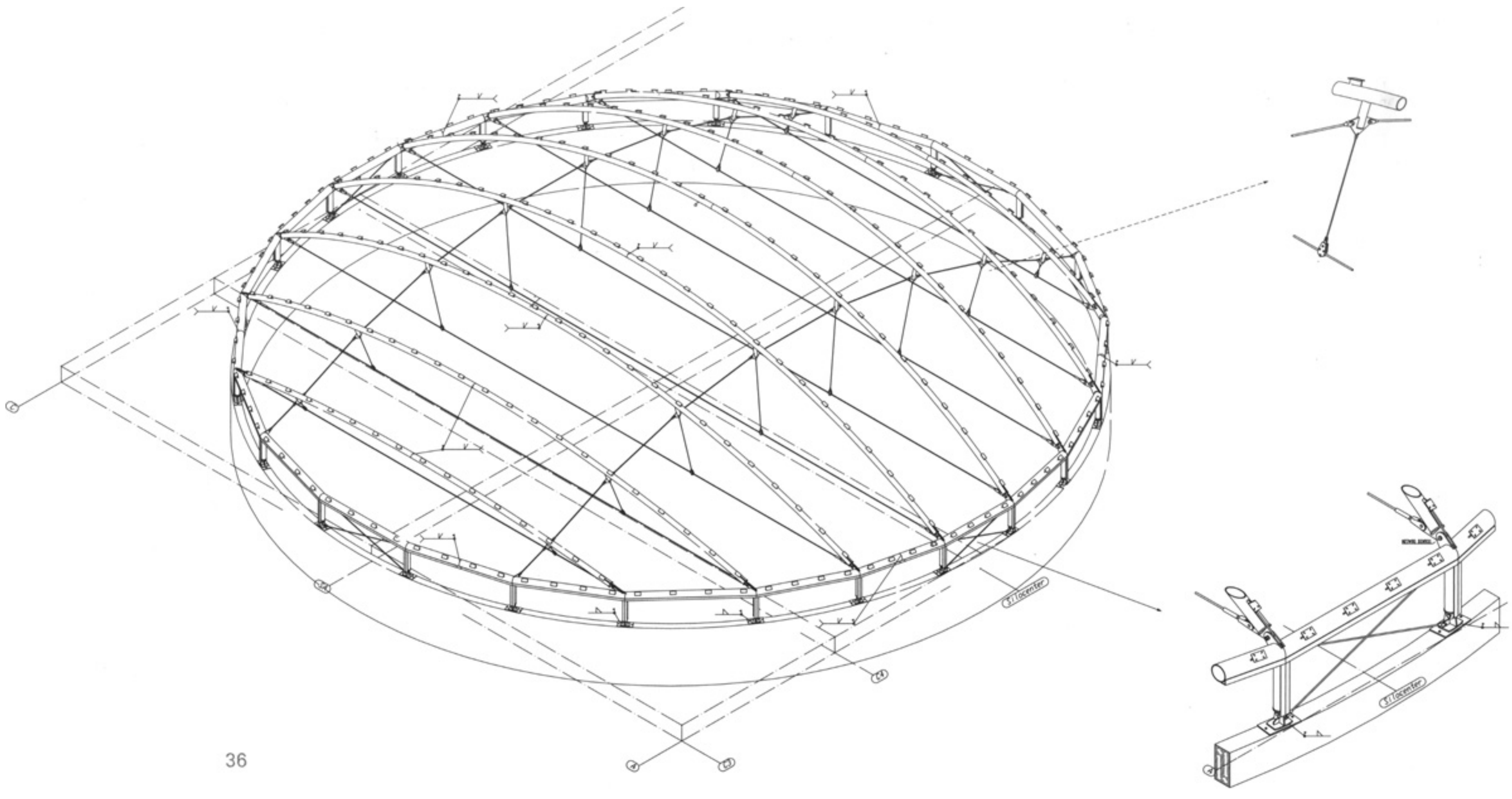
34–35__The form of the atrium roof is inspired by the efficient surfaces of soap bubbles. /

struts. Between these collars, longitudinal aluminium extrusions hold 11 ETFE cushions, with a maximum width of 4.8 meters, which extend the full length of the structure. The extrusions are connected at 6.1 meter intervals to an external cable net, which in turn is anchored to the structure of the former steelworks. In contrast with the Hampshire Tennis and Health Club, where the cables are pretensioned by steel struts and are merely deformed by the cushion envelope to develop their shape, the cable net at Magna only works when stressed by the ETFE cushions. When filled with air, each cushion seeks to minimize stress in the skin by becoming circular in section, or cylindrical in space. However, the cushions are deformed to a flat eye-shaped section by the cable net, which in turn is tensioned by that deformation. Both the cable net and the cushions require each other to develop their symbiotic form.

The structural role that air plays in this pavilion resonates with the theme of the exhibition, demonstrating the potential of new, lightweight technologies and evoking, through their juxtaposition with the heavy earthbound structure of the former steelworks, the same powerful contrast as the iconic 1901 photo of the airship at the Eiffel Tower – an image that, nearly a century later, is also conjured by Italo Calvino when he observes: "Were I to choose an auspicious image for the new millennium, I would choose...the sudden agile leap of the poet-philosopher who raises himself above the weight of the world, showing that with all his gravity he has the secret of lightness, and that what many consider to be the vitality of the times – noisy aggressive revving and roaring – belongs to the realm of death, like a cemetery for rusty old cars."[3]

The symbiosis of tension and compression, together with the ability of ETFE cushion systems to deflect and absorb movement, has been exploited to produce a very light primary structure for the atrium roof of the Oval at Baseler Platz in Frankfurt. This mixed-use development, which was completed in 2004, includes ground level retail, six stories of offices and three floors of residential units above. A bar building wraps the perimeter of its irregular site to create a free form central void, which becomes an atrium for the shops and offices and an external lightwell for the dwellings. The form of the atrium roof, inspired by efficient surfaces of soap bubbles, balances the desire for a flat roof that does not compromise the



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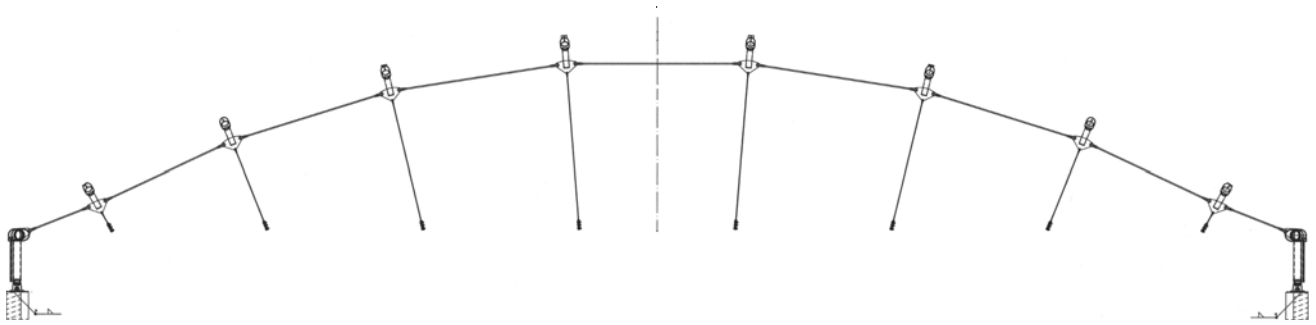

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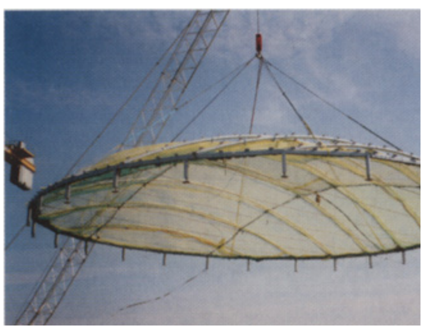
Frøsilo Flats, Copenhagen
MVRDV in cooperation with Jenson + Jorgenson + Wohlfeldt Arkitekter, 2005 /
36–37__The ETFE cushion roof is a cap sliced from a sphere, with bowstring trusses radiating from the sphere's center. /

outlook of the dwellings with the need to avoid ponding in the event of cushion deflation. The resulting slightly curved surface is sliced into parallel 3.5 meter wide bays, each of which is marked by a bowstring truss. Although the trusses have a consistent camber of 8 percent of their span, their variation in length from 10–30 meters results in unique curvature in each bay. The trusses comprise 219 millimeter diameter tubular steel top chords; V-shaped compression struts perpendicular to the top chords; and tension cables in both directions. Significant horizontal loads from the top chords are reduced both by the bowstring cables and by sliding connections to a perimeter ring beam that, under positive wind and snow loading, permit the cambered trusses to flatten. The ring beam translates the remaining horizontal loads into vertical loads supported by the surrounding building, thus enabling the design team to remove significant weight from the bowstring truss. Responding to wind uplift, the top chord of the truss goes into tension, acting like a cable instead of a beam. Under snow loads, it goes into compression, and the V-struts and tension cables prevent buckling. The struts and cables also provide lateral restraint, resisting the tendency of the pressurized cushions to pull the top chords of the trusses sideways. The enclosure consists of three layer ETFE cushions, which are warped in space to form-find the geometry of the surface.

The atrium roofs of Frøsilo Flats in Copenhagen, completed in 2005, work on the same principle. This residential scheme reuses redundant grain silos and, to avoid making large openings in the existing concrete walls, the flats are attached to the outer faces of the cylinders. The enormous voids of the silos, enclosed with ETFE cushion roofs, are transformed into dramatic entrance foyers and vertical circulation and services shafts. Each atrium roof is a cap sliced from a very large sphere and the trusses, instead of being parallel, radiate from the sphere's center. Consequently, bowstring cables run only parallel to the top chords. Perpendicular to the trusses, cables have been eliminated because the symmetrical geometry enables the foils themselves to work structurally to prevent the sideways bending of the top chords.

Regeneration of another historic artifact capitalizes on the ability of ETFE cushion systems to deflect by creating a large moveable structure. Meiderich Theater in Duisburg, completed in 2003, is an open-air venue located



38–42

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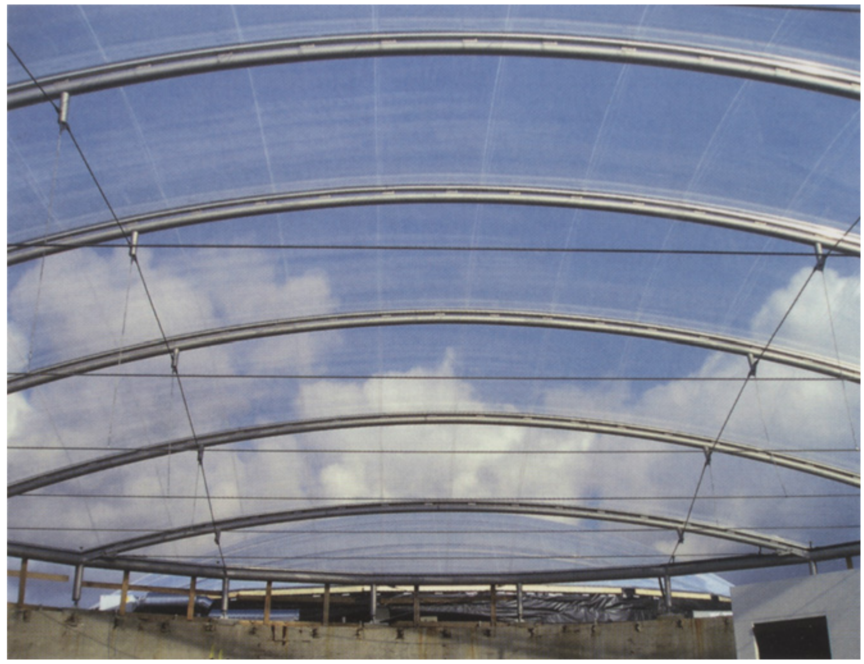

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38–42__The ETFE cushion roofs were prefabricated and craned into place. /
43–45__Bowstring cables are parallel to the top chords of the trusses. /

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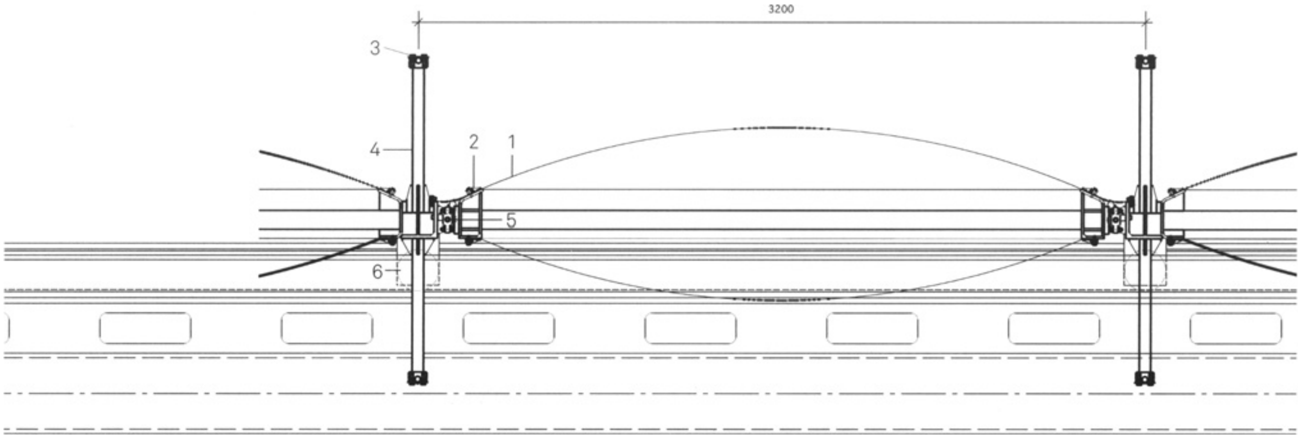
Meiderich Theater, Duisburg
planinghaus architekten, 2003 /
46–49__A retractable ETFE cushion roof for an open-air theater gives new life to a redundant ironworks. /



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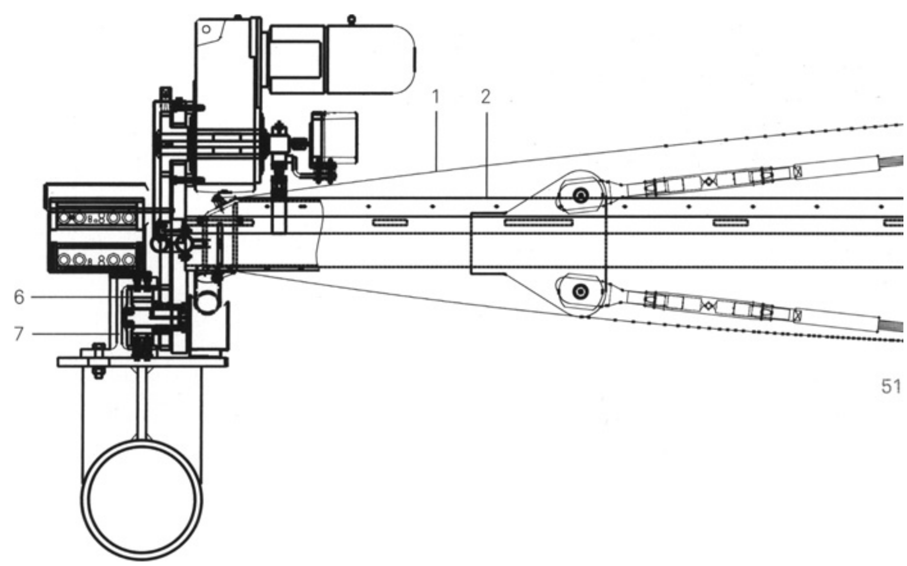

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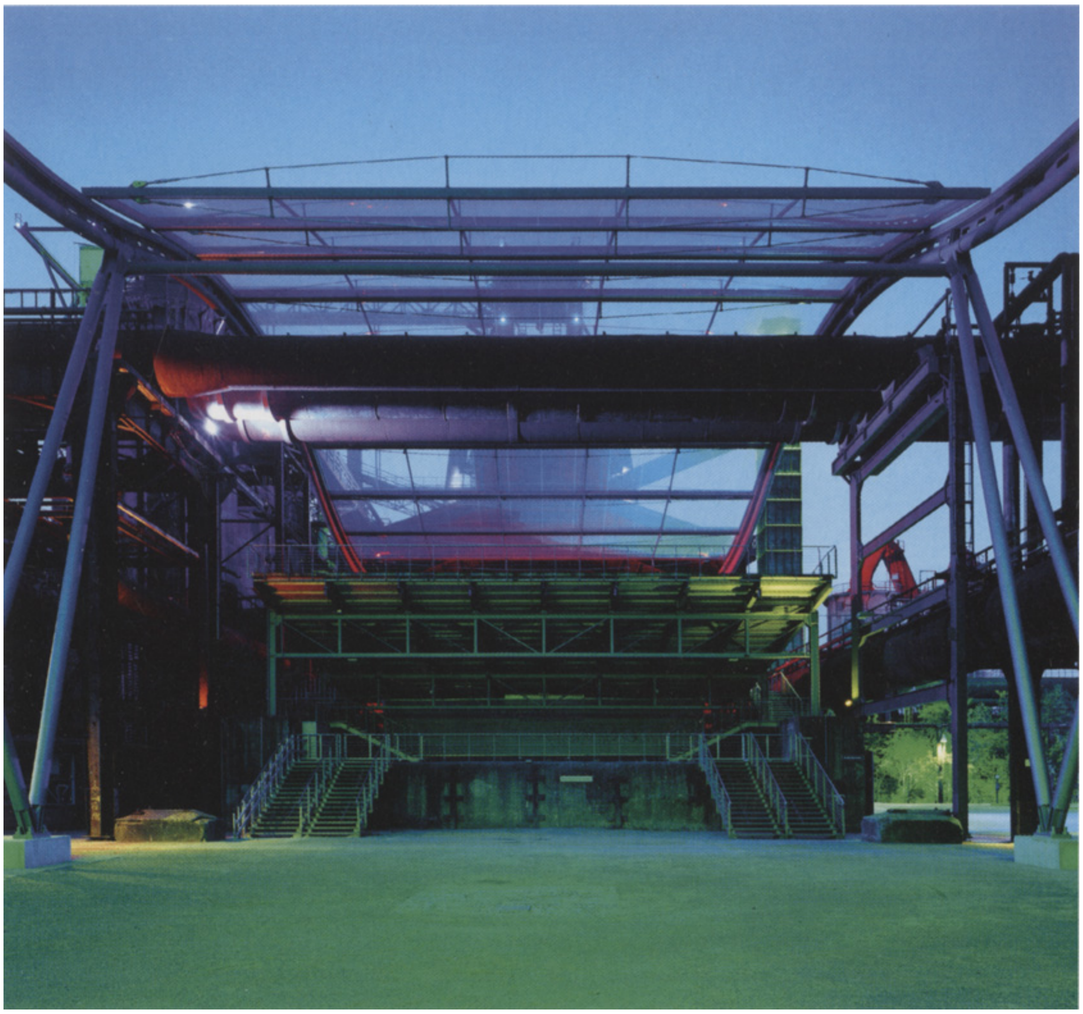
50__Longitudinal section detail /
51__Section detail at edge beam
1 200 micron transparent ETFE foil
2 extruded aluminium section with EPDM gasket
3 stainless steel rod
4 stainless steel support 50 x 50 mm
5 joint
6 movable wheel Ø 180 mm
7 guide rail /

in a 200 hectare park that, like the Magna project, transforms the wasteland of a former ironworks into a public amenity. A retractable roof, which ensures that the theater may be used in inclement weather, has three positions: above the audience seating, above an open-air foyer and within the adjacent shed of the casthouse, where it is stored during winter. This roof is carried by cable braced square steel tubes that roll along tubular steel beams stiffened by tees, which undulate to accommodate pipes and ducts of the former ironworks. The ETFE canopy is lightweight and can readily absorb deflection and movement, with the added benefit that the cushions improve the acoustic performance of the space. Because of the canopy's high degree of transparency, unimpeded views of the blast furnace are maintained, an important design consideration in this industrial archeological setting.

A larger scale of structure

In addition to these modest scale explorations, lightweight ETFE cushion systems and their supporting structures have the potential to achieve ever larger spans. A recently articulated structural concept, the xanadome, holds particular promise in this endeavor. In its simplest form, this very lightweight structure comprises a single articulated arch made of struts connected by ball joints that are held in space by two opposing fans of cables, with each fan radiating from a single anchor node to the arch nodes. Unlike a conventional arch that works purely in compression, here compression and tension are interdependent. This arrangement can be multiplied to produce complex geometric and non-orthogonal forms. With no bending forces, xanadomes use every component at full strength capacity. As theoretically efficient structures, xanadomes can potentially span further than more familiar structural systems, and it has been suggested that spans of up to a mile (1.6 km) are feasible.[4] At the same time, because the components are small, these structures are easy to fabricate, compact to transport and fast to erect, eliminating the need for scaffolding and large cranes. A xanadome with an ETFE cushion enclosure system was proposed in OMA's competition scheme in 2002 for roofing an entire urban block for the Los Angeles County Museum of Art.

However, the first large ETFE envelope to be realized utilizes a more familiar geodesic structure. Completed



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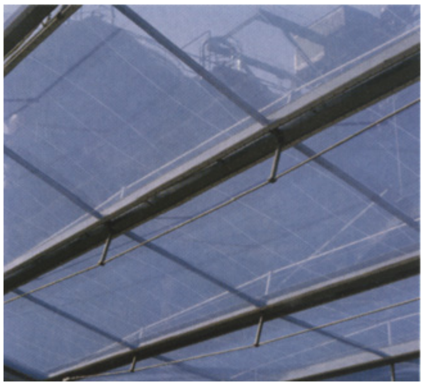

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52__The light weight of ETFE cushion systems and their ability to deform without adverse structural consequences creates new potential for large-scale moving structures. /
53–54__Transverse tubular steel beams are cable-braced. /

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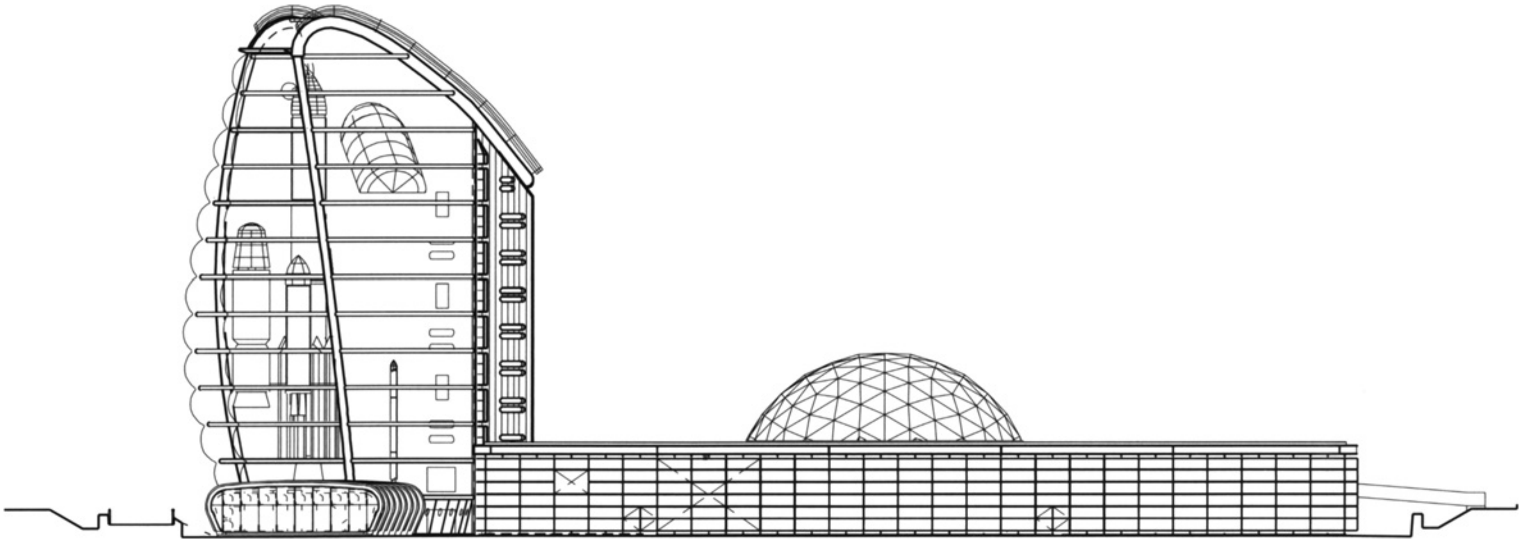

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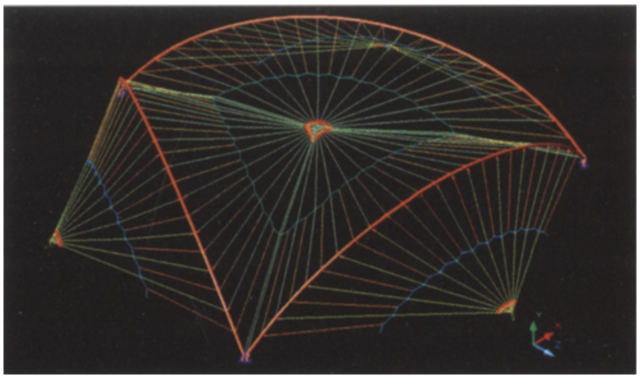
National Space Centre, Leicester
Grimshaw, 2001 /
55–56__The ETFE cushion envelope of the rocket tower – alluding to the recent history of bubbles and the Space Race – is supported by horizontal radiused tubes at 3 m centers, which in turn are carried by curved vertical tubes braced by a concrete core. /
57__Section /



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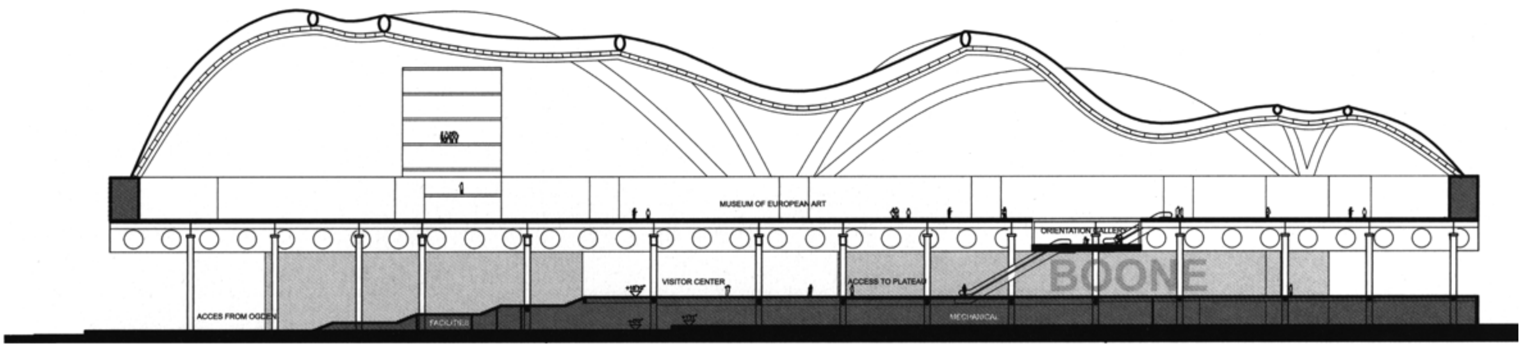

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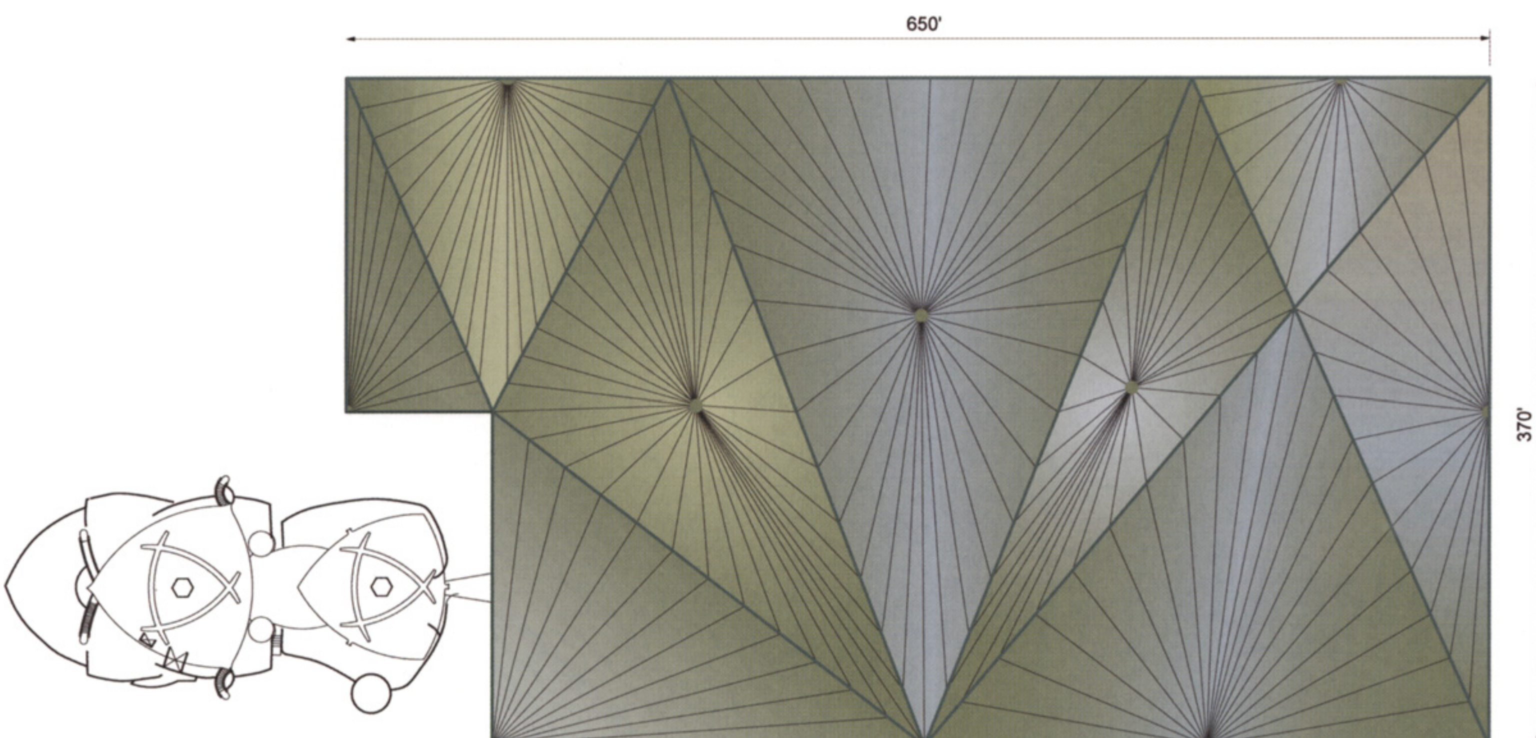

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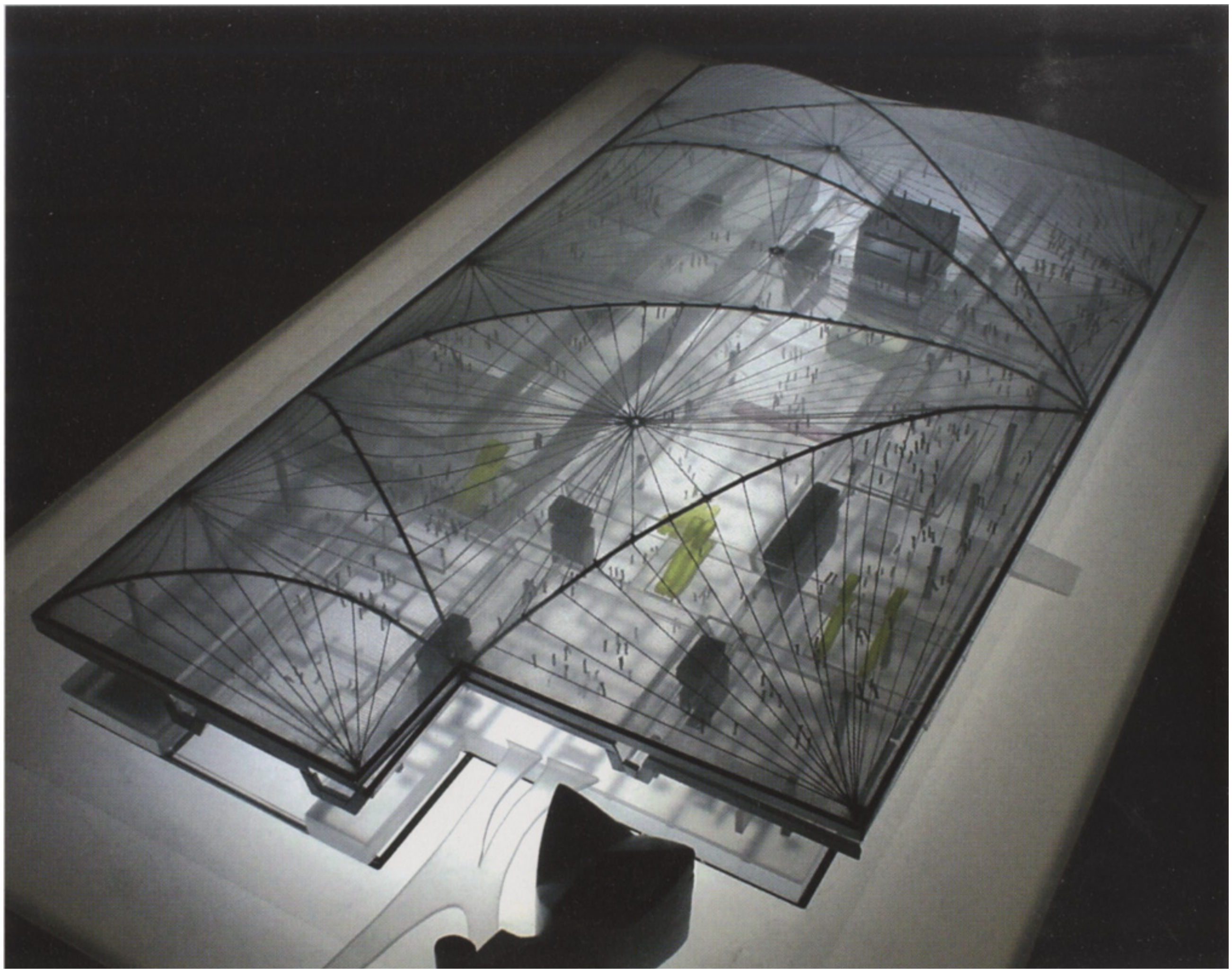
58__Balancing tension and compression, the xanadome
is an articulated arch stabilized by opposing fans of cables. /



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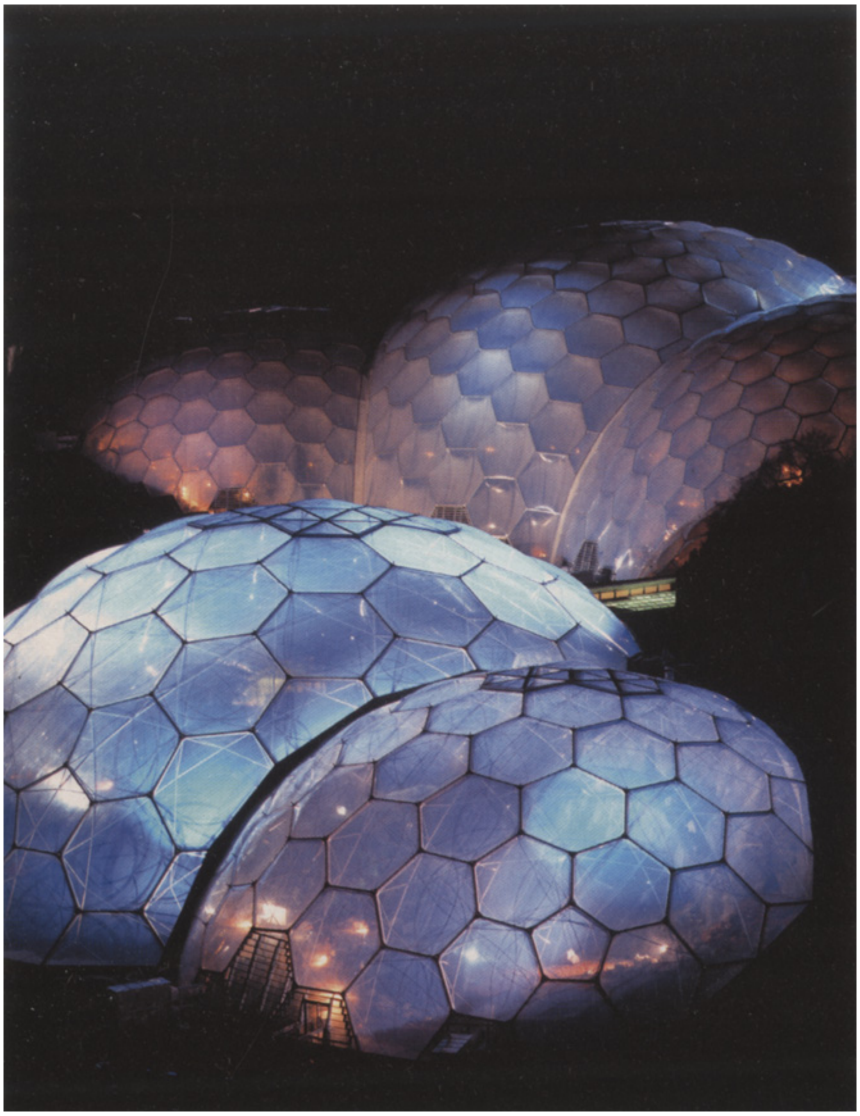
Los Angeles County Museum of Art
OMA, 2002 /
59__Section /
60__Roof plan /
61__OMA's competition scheme featured a xanadome structure and an ETFE cushion envelope. /

in 2001, the Eden Project seeks to highlight the interdependence of man and plant ecology, marrying the ideal of paradise with technological control of the environment. As the largest plant enclosure in the world, built in a reclaimed china clay pit in St. Austell, Cornwall, in southwest England, much has been written about this enormous environmentally responsible envelope. Aptly described as "...Buckminster Fuller meets polymer technology and the capabilities of computer modeling,"[5] the Eden Project was the first of a new generation of buildings that are being designed expressly for ETFE cushion systems and which without the soft structural attributes of ETFE would not be technically feasible. Frei Otto should also be credited, for the eight intersecting domes, which range in radius from 18–65 meters, nestle in the landscape like a chain of soap bubbles enclosing maximum volume with minimum surface area.

To meet the client's requirement for maximum transparency for plant growth, structural elements had to be minimal in size and number. A double glazed envelope, in addition to requiring a hefty primary structure to support its significant weight, plus secondary structure to deal with small glazing modules, was simply not compatible with this requirement. ETFE cushions, with their light weight and large size, proved to be ideal for the task. After studying many geometrical configurations, the design team adopted Fuller's geodesic structure – which evenly distributes structural members and can be scaled to different dome radii to give optimum cladding panel sizes – and proposed a single layer unbraced geodesic using 500 millimeter diameter circular steel tubes. Although steel and cladding were tendered as two packages, Mero was appointed for both and, importantly, their bid proposed an alternative two layer hex-tri-hex geometry that significantly pared down the size of the structural members to 193 millimeters in diameter for the outer layer and 114 millimeters for the inner layer. The weight of the primary structure was thus reduced by 50 percent. With considerable cost attaching to nodes and edge detailing of cladding panels, the next objective was to develop the largest possible envelope components.

The design team faced significant challenges in equipping this lightweight steel structure and ETFE cladding system, together weighing 22 kilograms per square meter



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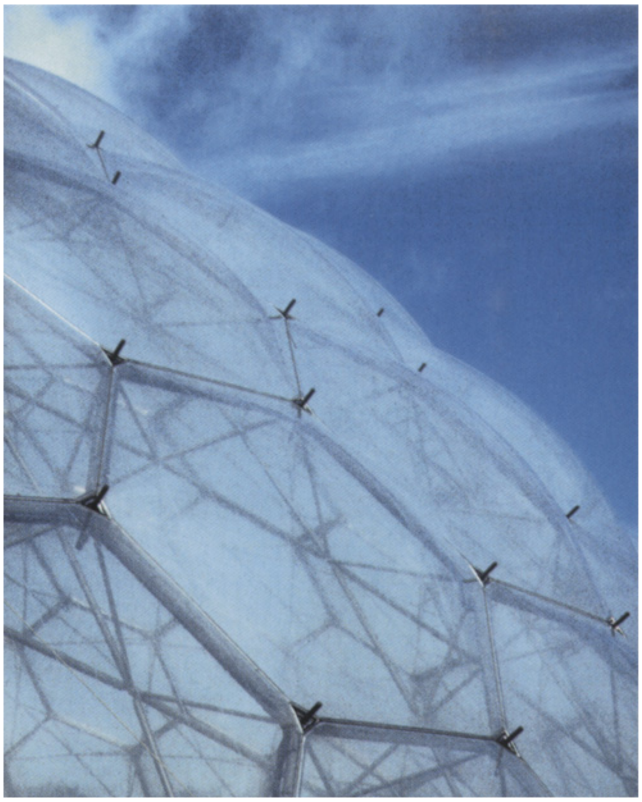

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of surface area, to deal with dynamic loads. While it was initially feared that wind loads on such a large surface area would make the project unbuildable, wind tunnel tests demonstrated that the clay pit's topography shelters the biomes from extreme winds, particulary positive pressures at low level. Cushion sizes are scaled to suit each dome using hexagons ranging from 5–11 meters in diameter. Because of these varying sizes and the geometric nature of geodesic domes, it is impossible to align modules where the domes intersect, so this junction is resolved by tubular steel lattice arches along the lines of intersection that pick up all nodes.

Because the ETFE cushions at Eden were the largest that Vector Foiltec had built at that time, the contract included full-scale mock-ups and physical testing. Notwithstanding the sheltering topography, it was initially thought that cable net reinforcement would be generally required to deal with heavy wind, rain and snow loads. Through mock-up testing, the rise of the cushions was modified by innovative patterning and load sharing outer foils were developed so that the cable reinforcement could be omitted. The most critical wind loads are negative pressures on the outer layer of foil, which could be resisted either by thickening the foil or increasing the rise of the cushions. However, foils above 250 microns in thickness become brittle, and a cushion camber in excess of the usual 10–20 percent of span can adversely affect lateral stability under transverse loads. Instead, the outer layer of the cushions comprises two vacuum laminated thin foils, which are much stronger than a single membrane. To deal with snow loads and positive wind pressures, the camber of the innermost layer of the cushion, which has no transverse load exposure, is increased to 15 percent. The normal inflation of the cushions is 250 Pa but can be increased to 400 Pa to prevent deflation in heavy snow. The cumulative result of these adjustments is that cable net reinforcement is required only under cushions in the valleys of intersecting domes to cope with drifting snow. Despite the repetitive nature of geodesic geometry, each ETFE cushion is unique, with the number of foils, foil thicknesses, shape and rise tuned to the particular loads each cushion must carry.

The Eden biomes work through a combination of bending stiffness and shell action between the inner and

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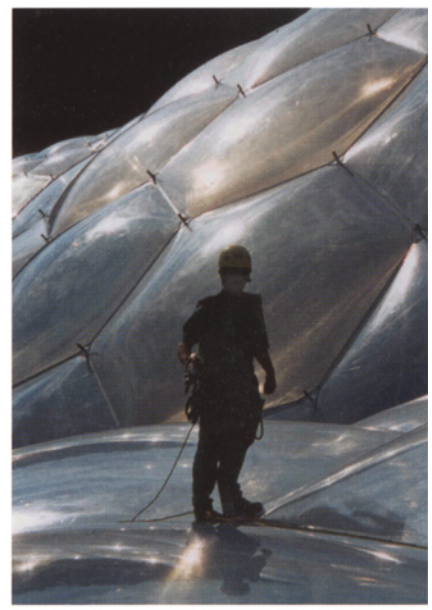

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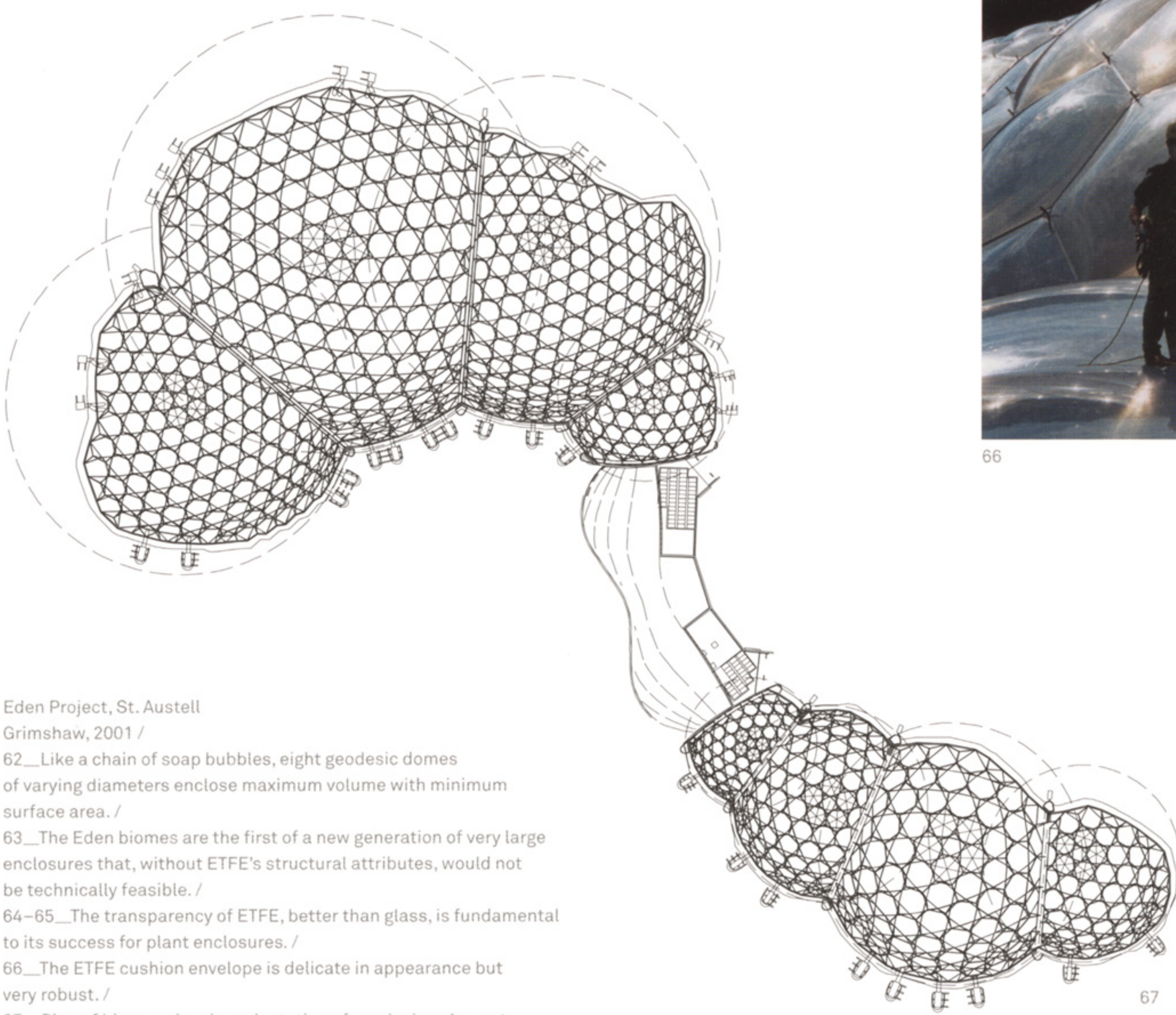

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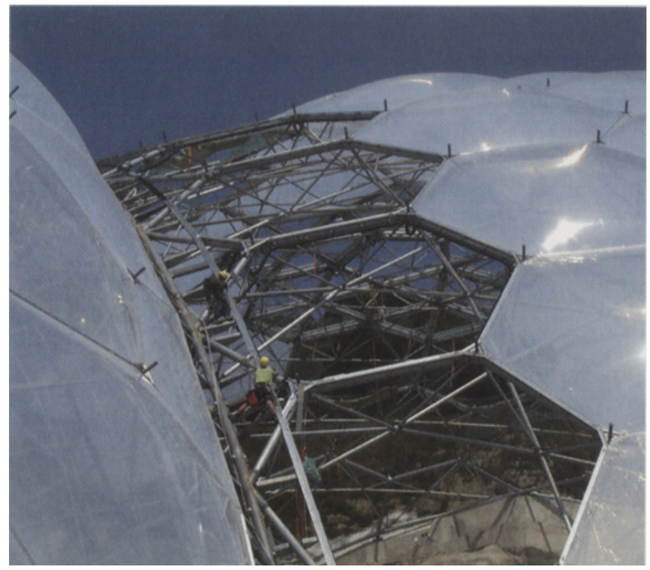
Eden Project, St. Austell
Grimshaw, 2001 /
62_Like a chain of soap bubbles, eight geodesic domes of varying diameters enclose maximum volume with minimum surface area. /
63_The Eden biomes are the first of a new generation of very large enclosures that, without ETFE's structural attributes, would not be technically feasible. /
64–65_The transparency of ETFE, better than glass, is fundamental to its success for plant enclosures. /
66_The ETFE cushion envelope is delicate in appearance but very robust. /
67_Plan of biomes showing adaptation of geodesic spheres to site topography /



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68__The biomes have opening cushion vents at the apex of each dome. /
69__Lattice arches pick up nodes at dome intersections. /
70__As the largest plant enclosure in the world, the structure and ETFE cushion envelope weigh less than the air enclosed by the biomes. /

outer layers of the geodesic structure. Because of the shell mechanism, there are no expansion joints, even in the largest 250 meter long biome. Structural deflections of up to 200 millimeters, which are normal for long span structures, are readily absorbed by the pliable ETFE envelope. The entire structure and skin weigh less than the air the biomes enclose, an accomplishment that would surely rank highly on Buckminster Fuller's index of environmental efficiency and a significant achievement at a moment when human beings are beginning to think seriously about the need to touch the earth lightly.

1__ Craig Schwitter. "Use of ETFE foils in lightweight roof constructions," *Proceedings of the IASS-ASCE International Symposium 1994 on Spatial, Lattice and Tension Structures*, p. 625.
2__ Reyner Banham. "Monumental Wind-bags," as reprinted in *The Inflatable Moment* (New York: Princeton Architectural Press and The Architectural League of New York) 1999, p. 33. This article was originally published in *Arts in Society* (18 April 1968) pp. 569–570.
3__ Italo Calvino. "Lightness," *Six Memos for the Next Millennium* (New York: Vintage International) 1993, p. 12.
4__ Xanadome brochure, p. 18.
5__ Michael Wigginton. "Eden Regained," *Architecture Today* (June 2001), p. 119.


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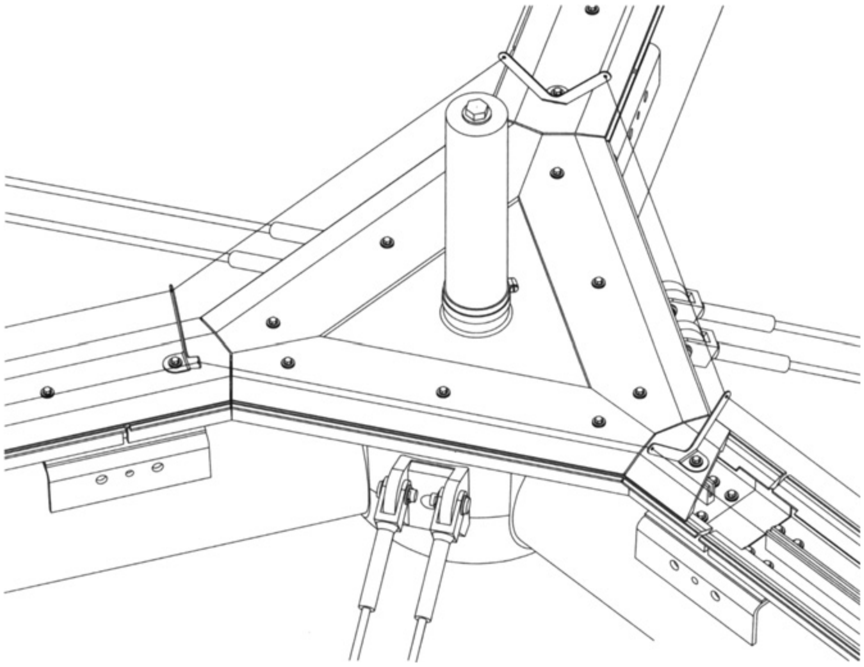

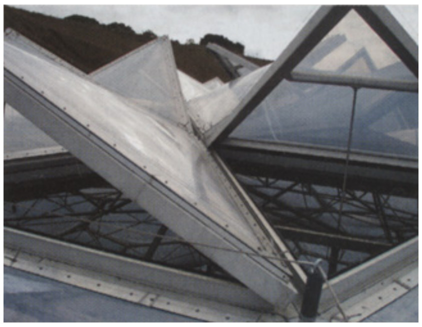
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71__Testing of full-scale mock-ups resulted in the introduction of load sharing foils, minimizing the need for cable reinforcement under the ETFE cushions. /
72__Opening vent frames fixed to geodesic structure /
73__Node detail /
74__Cushions range from 5–11 m in diameter. /
75__Edge extrusions for ETFE cushions are fixed directly to the primary structure. /
76__Opening vent /
77__The two layer hex-tri-hex geometry of the domes significantly reduced the member sizes and weight of the primary structure. /

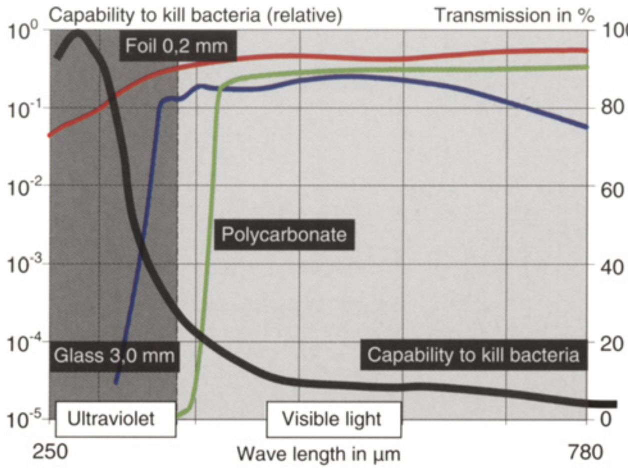
The Performative Skin

In addition to speculating about highly serviced minimal membranes as a technological version of paradise, Reyner Banham was an advocate of the well-tempered environment and of the integration of environmental services into architectural thinking. This interest in servant space is further developed in the book *Material Misuse*, in which architect Sheila Kennedy identifies the evolution from solid to hollow forms of wall construction, and the subsequent accommodation of services in the resulting interstitial space, as a pivotal shift in architecture. Although ETFE cushion systems might be accurately described as "98 percent nothing,"[1] these hollow assemblies comprising interstitial air and a thin enclosing membrane are minimalist workhorses, with their considerable structural attributes complemented by multi-faceted environmental servicing capabilities.

Light and view

In addition to being lightweight, the primary characteristic that has popularized ETFE, particularly compared to other membrane materials, is its transparency. With color rendering comparable to daylight, it transmits total light at a rate of 90–95 percent and ultraviolet light at 83–88 percent, both significantly better than glass. Its transparency to ultraviolet light has been instrumental in its adoption for large botanical enclosures. Because ultraviolet light kills bacteria and fungi, ETFE enclosed biospheres can be operated as organic, self-sustaining ecosystems without the need for chemical interventions, such as pesticides, that are required in glasshouses.

It also has high absorption in the infra-red range, which can reduce energy consumption by exploiting the greenhouse effect, where short wave radiation is re-radiated as long wave and trapped. For all of these reasons, ETFE is increasingly being used as an alternative to glass in all kinds of applications. However, although better than glass in terms of light and solar transmission, ETFE is 1.5–3 percent diffuse[2] which makes objects viewed through the foils look slightly milky. This effect interestingly is not apparent when looking at the sky and, as the use of ETFE in buildings increases, manufacturers are rapidly improving the optical quality of the foils. A foil has recently been introduced that has optical transmission comparable to glass.[3]



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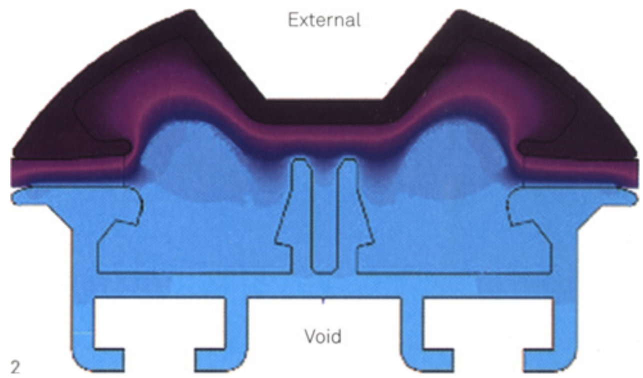

1__Transparency: Glass in comparison with ETFE and polycarbonate /
2__Extrusion with thermal break; thermal insulation performance is good at both the cushion's edge and its center. /

Heat and ventilation

In addition to working structurally by stressing foils and damping cushions from wind-generated movement, the air in cushion systems provides a layer of insulation that enhances the thermal performance of the building envelope. It might be assumed that the variable thickness of cushions suggests an uneven thermal performance. However, because an inflated cushion of just 10 millimeters in thickness performs well thermally, the relative thinness of cushion edges has little detrimental impact. EPDM (ethylene propylene diene monomer) gaskets incorporated in the perimeter aluminium extrusions perform a number of roles. In addition to sealing joints, they relieve stress from the keder edge detail and create a thermal break. This thermal break, together with insulation incorporated in the extrusions, effectively eliminates cold bridging.

The process of heat transfer through transparent envelopes is complex, consisting of a number of interactive phenomena: conduction, convection, radiation, surface emissivity and energy loss through leakage. The thermal performance of transparent systems is related to their ability to insulate the envelope and to optimize solar shading. ETFE foil cushions allow all of these criteria to be manipulated to tune the overall performance of the envelope. The material itself is a good heat insulator. In cold weather, even with the same U-value, the thermal comfort level of ETFE cushions, with their warm inner surface typically close to the ambient interior temperature, is much better than glass. Convection can be controlled by the number of air cavities in the system with U-values ranging from approximately 2.94 $Wm^{-2}K$ for a two layer cushion to 1.18 $Wm^{-2}K$ for a five layer assembly. The lack of air infiltration through a cushion envelope increases the U-value by approximately 0.35 $Wm^{-2}K$. Furthermore, the large area-to-edge ratio of ETFE cushions as opposed to glazed envelopes significantly improves the overall performance.

Each layer of a cushion can be customized. Both radiation and solar shading can be controlled by incorporating translucent or opaque chemical pigments in any or all of the foil layers, or by printing any of the surfaces with similar pigments to change their radiation transmission characteristics, achieving a wide range of shading coefficients. Printing is also used to reduce surface emissivity, or the ability of a body to absorb and/or radiate energy. Ongoing

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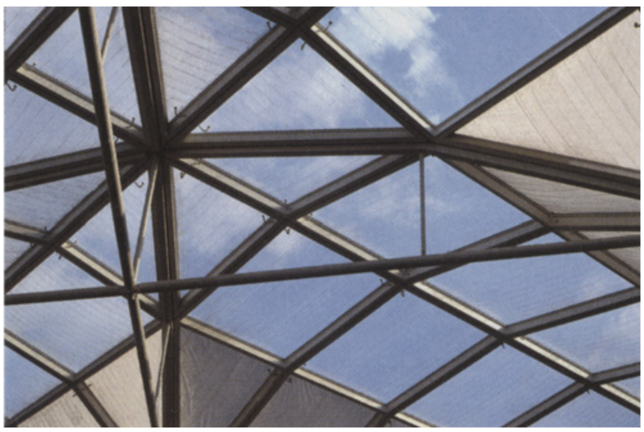

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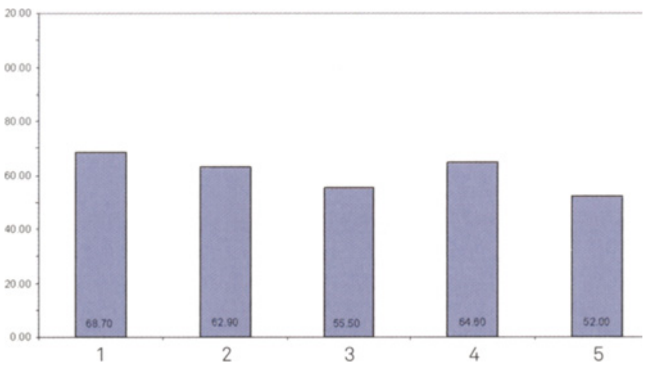
Chelsea and Westminster Hospital, London
Sheppard Robson, 1990 /
3–5__An early application of ETFE for atrium roofs played an important role in the building's passive servicing strategy. /

experiments use sputtered metallic depositions in much the same way as the glazing industry. However, surface emissivity plays a much smaller role in the overall effectiveness of an ETFE cushion's insulative properties because the surface-to-material volume ratio is so much better than for a glazed envelope. Because ETFE foil is thin and is the same temperature as the air adjacent, its ability to absorb or radiate energy is not critical, unlike glass which gets much hotter as it absorbs solar energy. Therefore, the need to manipulate the absorptive character of the surface is much less significant for the envelope's environmental performance. In addition to energy lost or gained through the envelope, energy lost through air leakage is virtually eliminated because cushion systems, which are pressurized and have vastly reduced numbers of junctions, effectively operate as a barrier to any air movement through the envelope. In thermal terms, the prevention of heat losses due to infiltration significantly decreases the building energy footprint, equivalent to moving from triple to quadruple glazing.

These pressurized enclosures, unlike their air-supported predecessors, do not rely on airlocks for structural stability. Like conventional building enclosures, ETFE cushion envelopes can therefore incorporate natural ventilation via operable louvers and opening cushions. The ETFE atrium roof of the Chelsea and Westminster Hospital, a building designed nearly 20 years ago, significantly reduces the area of external wall and helps to heat and cool the building using sunlight and opening vents to induce natural stack effect ventilation. This passive strategy minimizes energy consumption and reliance on mechanical systems. Unlike conventional envelopes, because ETFE is soft and can withstand large deflections, very large vents and moving structures can be engineered in ways that are not feasible using conventional technologies. As at the Meiderich Theater in Duisburg, roof and enclosure systems can also be designed to move and hinge, allowing the inside to become outside on demand.

Sound

The fact that ETFE cushions are made from membranes whose thickness is measured in microns means that this kind of building envelope has effectively little or no mass. Similar to its soft structural attributes, ETFE cushions are



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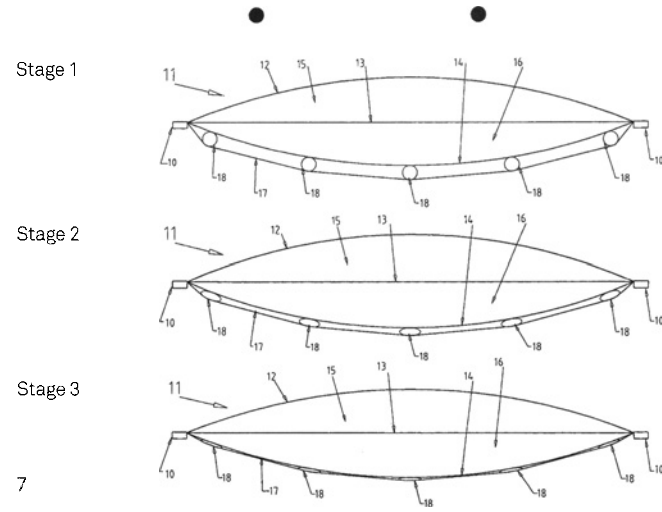

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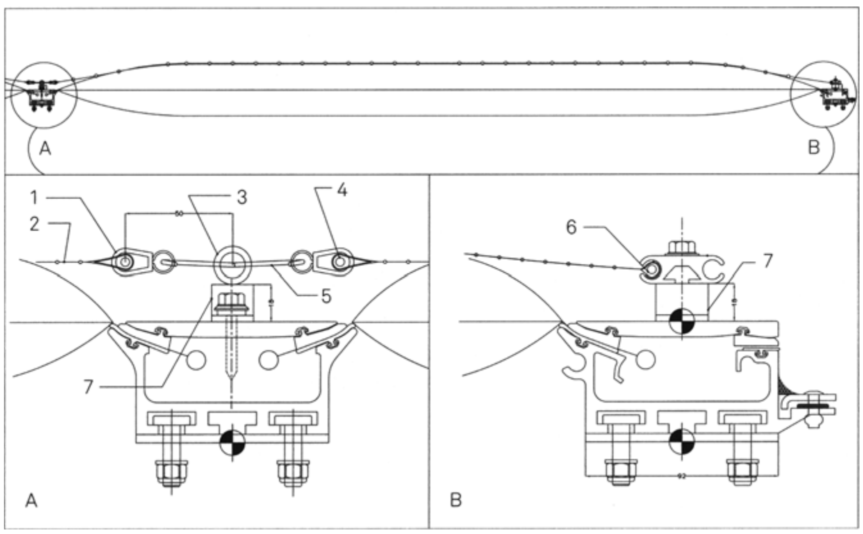

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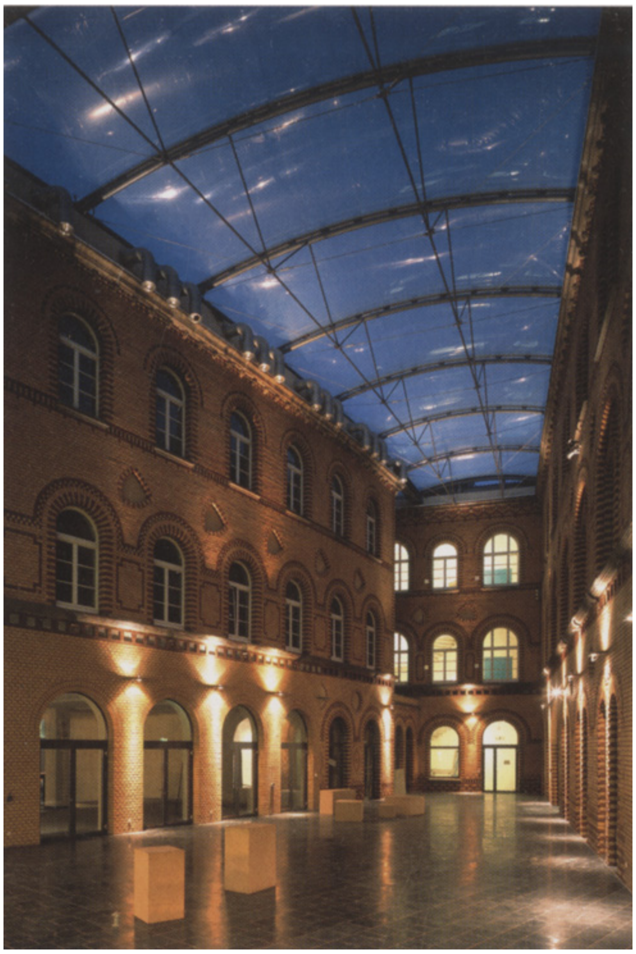
6__Sound intensity level under moderate to heavy rain (40 mm/hour)
1 ETFE
2 ETFE RS1
3 ETFE RS2
4 25 mm polycarbonate
5 double glazing /
7__Interior acoustic performance of ETFE cushion systems may be modified by a microporous layer that can be pneumatically manipulated for selective frequency absorption. /
8__Rain noise may be suppressed by a layer of net or mesh on the external surface of the cushion. Rain suppresser fixing detail
1 shackle
2 rain suppresser mesh
3 eye bolt bracket
4 fiberglass rod
5 nylon rope Ø3 mm
6 prefixed polyethylene keder
7 top hat bracket /

acoustically soft, particularly to low frequency sound. They offer little resistance to sound energy, which passes straight through the cushions. From the point of view of room acoustics, the cushions absorb rather than reflect internally generated noise and thus create more comfortable internal environments than acoustically hard materials like glass. For environments where the absorption of medium or high frequency sound is critical or where the acoustic environment is particularly sensitive, a kind of Helmholtz resonator can be added to the cushion system. This consists of a microporous ETFE layer on the underside of the cushions that, through pneumatic manipulation of air-filled tubes, can be tuned to selective frequency absorption.[4]

In contrast to their superb performance with regard to room acoustics, ETFE cushions provide little or no sound reduction to externally generated noise. The surface of the cushions is excited by heavy rain, for example, and transmits this impact noise. In many applications, such as atria, leisure and shopping centers, this acoustic awareness of changing weather is considered to be a positive attribute. However, for spaces like offices and libraries that require very quiet interior conditions, this may be dealt with by a rain noise suppression system that consists of a net or mesh, which is laid over the external surface of the cushions and works by reducing the water flow from the roof to create a thin layer of water over the skin.[5] This has two effects, both increasing the mass of the envelope to reduce its sound transmission qualities and acoustically dampening the impact of the raindrop itself.

Building regeneration through passive servicing strategies

ETFE cushion systems are increasingly being deployed in the refurbishment of historic buildings both because of the structural benefits of these lightweight envelopes and their contribution to passive environmental servicing. Her Majesty's Treasury in London, constructed in 1917, is a listed historic building. Its cellular offices and endless corridors were failing to meet contemporary office needs, and the redevelopment of the premises, completed in 2002, focused both on removing walls to create open plan, naturally ventilated workspaces and on transforming previously unused lightwells into the public and social elements of



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Kapuzinercarrée, Aachen
Ingenhoven Overdiek + Partner, 2002 /
9–10__The use of ETFE cushions instead of glass significantly reduced the loads imposed on this historic building and improved its environmental performance. /

the program. These five story voids, now capped with triple layer printed ETFE cushion roofs, house a new entrance atrium, staff training facilities, a library and a café. As a consequence of these changes, the building's net efficiency has increased dramatically, and the Treasury is now housed in just half of the building, freeing up the remainder for other government departments.

The enclosed lightwells, in addition to capturing valuable new space, are essential to the building's environmental services strategy. Due to the reduction of external wall area, energy demands for the building have decreased. A considerable increase in reflected daylight has been achieved by cleaning the Portland stone façades in open courtyards and the white-glazed brickwork in lightwells. The amount of natural daylight entering the office spaces has been significantly improved by the removal of bomb-blast curtains from 1800 windows, which was made feasible by rebuilding window frames to minimize danger of splintering during an explosion. The enclosed lightwells also act as thermal chimneys. By opening windows, fresh air from the outer faces of the building is drawn inside and waste air escapes into the lightwells, where it rises and is released by conventional perimeter vents at high level. This pattern of air movement is assisted by the ETFE roof, which creates a pressure gradient to draw air through the building, so providing extra ventilation. The building's reduced energy footprint sets improved environmental standards for government buildings in the UK and demonstrates ways in which historic buildings can be upgraded to embrace sustainable strategies.

Urban regeneration through passive servicing strategies

The environmental performance of ETFE cushion systems is also being deployed at an urban scale. Southern Cross Station in Melbourne was completed in 2006. As the only station in Melbourne that connects regional, intercity and national train services with local public transport, Southern Cross is effectively Melbourne's central station. Completely revamping a former down-at-heel station and featuring a dramatic roof that is rapidly becoming a landmark in the city, the terminus is also the focus of a mixed-use office and retail development that is intended to regenerate a neglected former industrial zone at the edge of the central business district.


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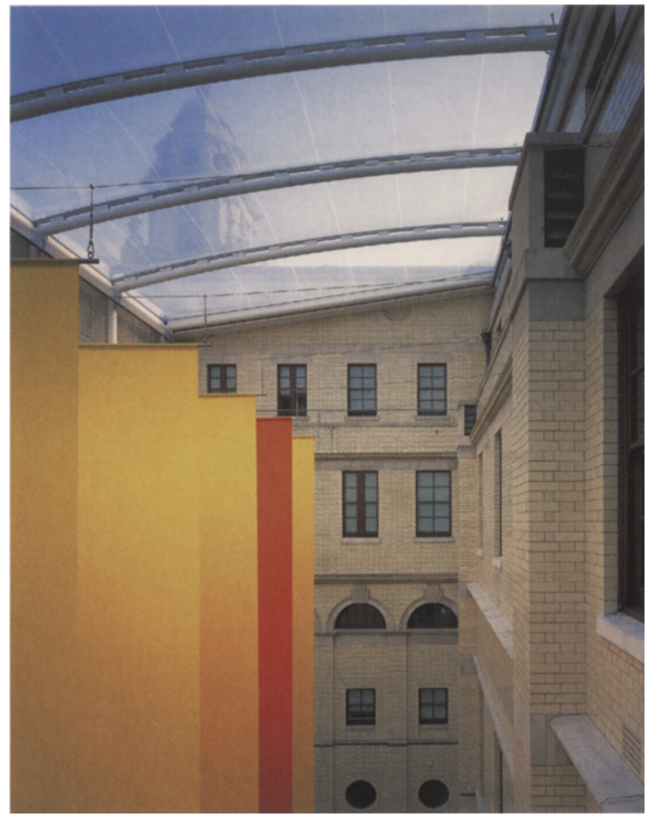
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Her Majesty's Treasury, London
Foster and Partners, 2002 /
11–14___ETFE roofs have transformed former lightwells into staff amenities and play an integral role in a passive servicing strategy that raises the bar for environmental performance of UK government buildings. /

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National Gallery, London
Purcell Miller Triton, 2003 /
15–17___ETFE cushion enclosures provide a lightweight, transparent, watertight and highly insulated second skin above the museum's original skylights. /

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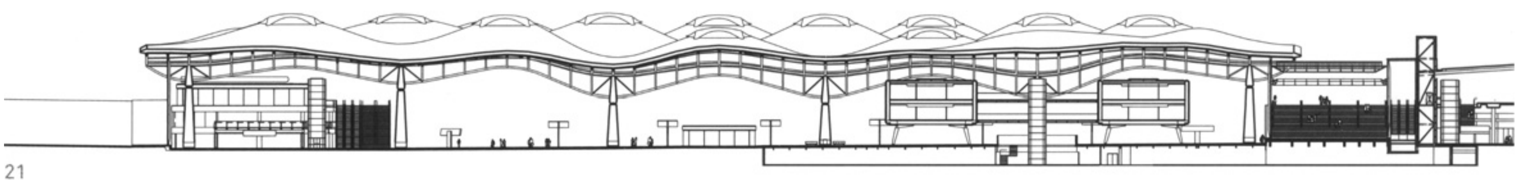
Jean-Paul Gaultier Headquarters, Paris
Alain Moatti + Henri Rivière, 2004 /
18–20__ETFE cushions have been used to replace glass skylights, creating the illusion of occuli open to the sky. /



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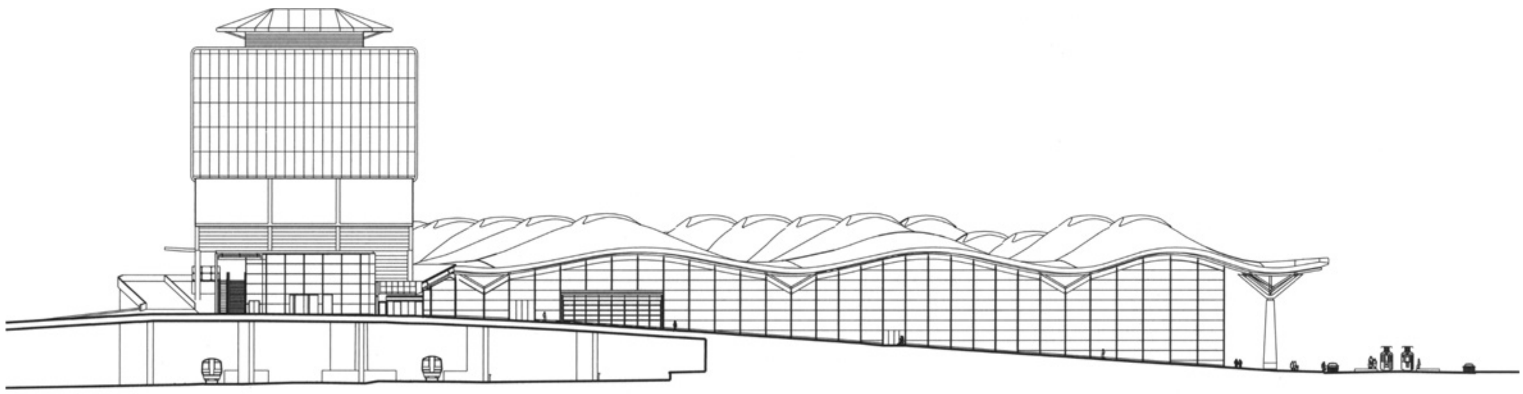


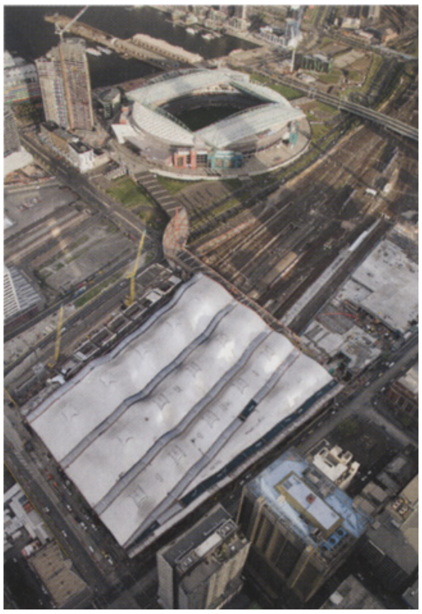
22

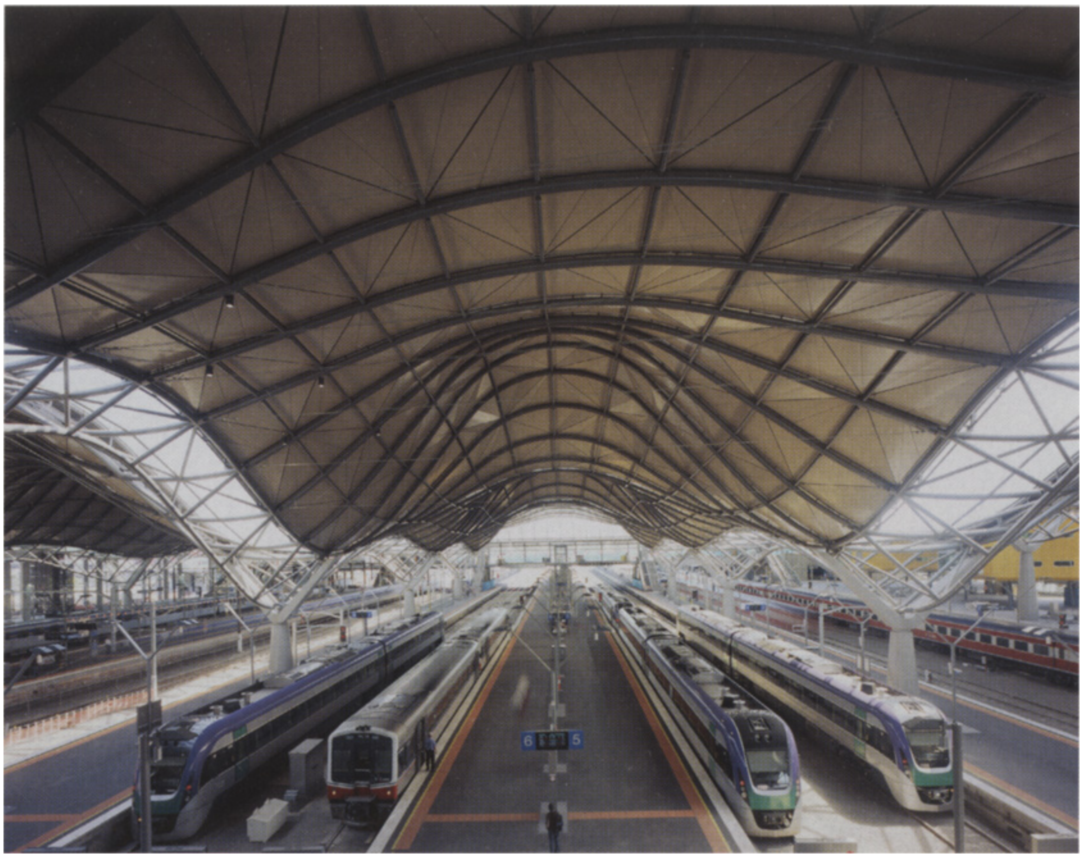
Southern Cross Station, Melbourne
Grimshaw, 2006 /
21__Longitudinal section /
22__Elevation /

The station's roof is a product of environmental performance requirements that were central to the client's brief. Apart from the opening for trains, the terminus is enclosed on all sides by glazed façades. In Australia's extremely hot climate, the 37,000 square meter roof, which covers an entire city block, provides an urban shade canopy. Like sand dunes, its form has no repetition or symmetry. The high zones act as reservoirs for hot air, smoke and diesel particles, which are naturally extracted through louvers at each apex that work in tandem with prevailing winds. These winds also define the valleys across the roof, which are slightly offset both from the city's grid and the alignment of the train platforms to ensure effective natural ventilation throughout the year.[6] Costly mechanical extraction systems have thus been eliminated.

The roof structure is a two-way welded net of 356 millimeter diameter steel tubes on an irregular grid that accommodates the track layout. Although constant in their external diameter, the tube walls vary in thickness, becoming more robust to deal with areas of flatter curvature. This continuous net is supported on undulating triangular steel spine trusses, which in turn are carried by giant Y-shaped fabricated steel plate columns at approximately 40 meter centers. The spine trusses, 8 meters wide at the top, vary in depth from 4 meters at the columns to 2 meters at mid-span. Clad with standing seam aluminium roofing and triangular insulated aluminium ceiling panels, the quadrilateral mesh is stiffened by diagonal bracing that is concealed above the ceiling in a void that also serves as a plenum for the station's natural ventilation.

To counteract the large-scale and massive character of this structure, continuous ribbons of ETFE skylights above the spine trusses fill the station concourse with natural light. ETFE was chosen because of its ability to span with minimal structure and the ease with which it can accommodate a complex geometry. The roller coaster form of the skylights is defined by 5 meter wide and 20 meter long ETFE cushions. Junctions between cushions are at low points, where reduced cushion camber, gutters and siphonic drainage all help to prevent ponding. While glazing would have required a robust supporting structure and complex movement joints, the two layer clear ETFE cushions reduce the load on the steel structure and augment the roof's illusion of transparency and lightness. These skylights also





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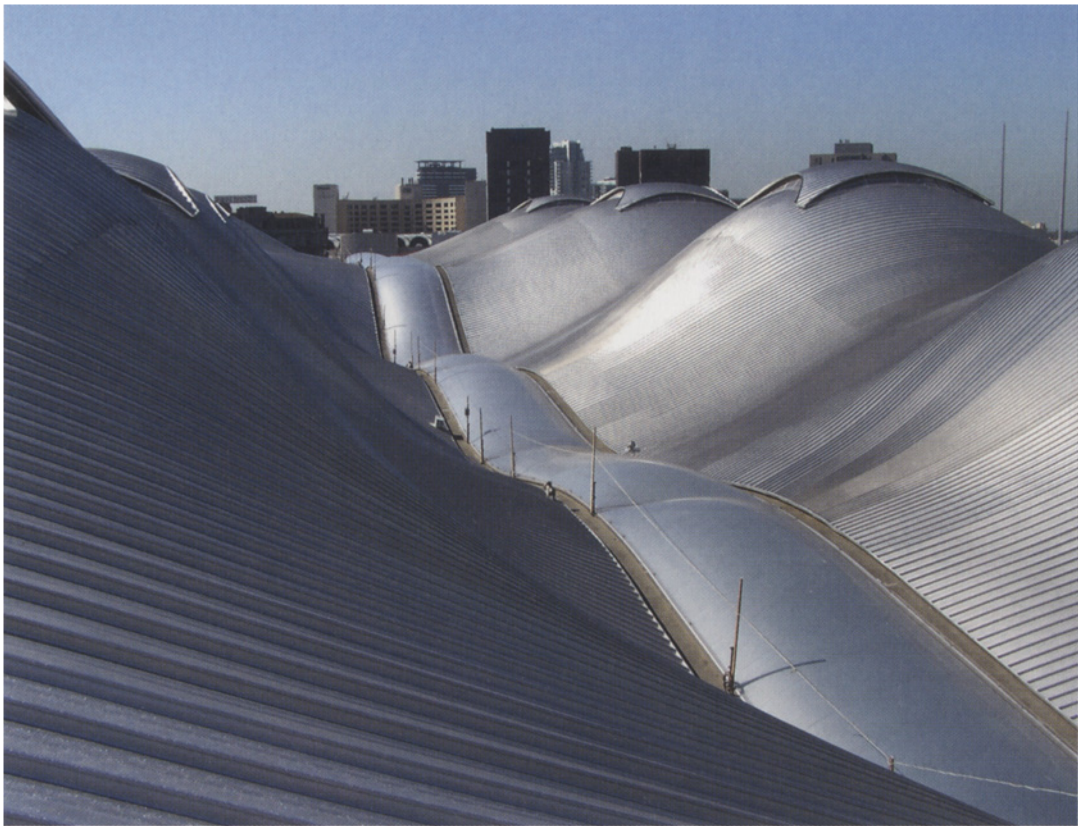
23–24__The alignment of the "sand dune" roof works with prevailing winds to induce natural ventilation, eliminating the need for mechanical extract systems. /
25–26__Undulating steel trusses, clad with ETFE cushion skylights, support a double curved net of welded steel tubes. /



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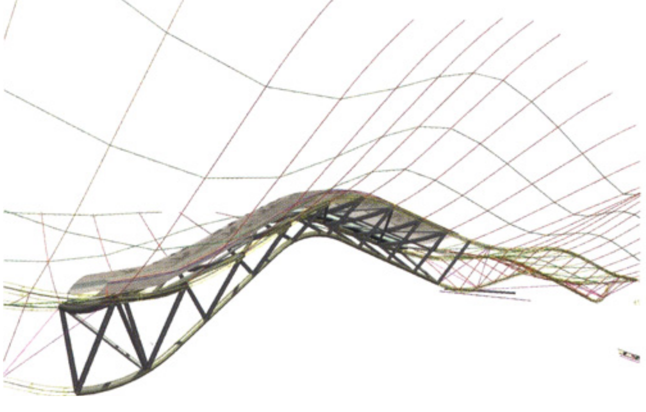

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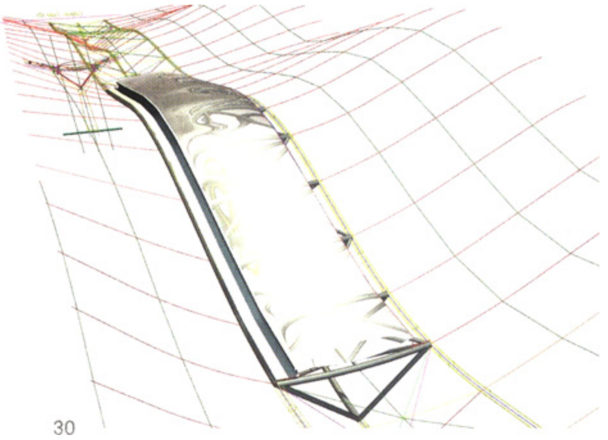

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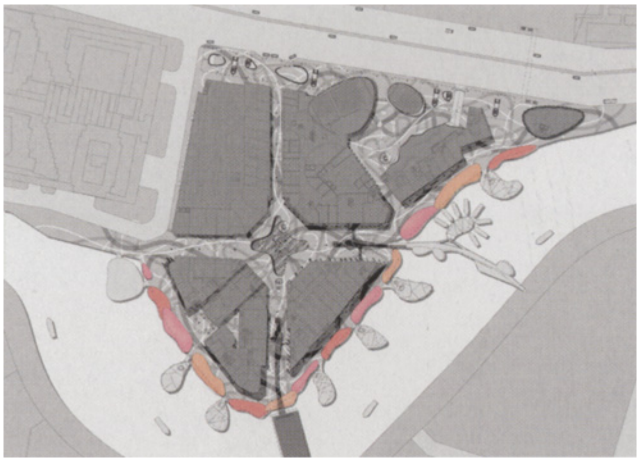
27–30__Ribbons of ETFE cushion skylights ensure the continuity of the roof's geometry and, as soft structures, adjust readily to dynamic loads. /



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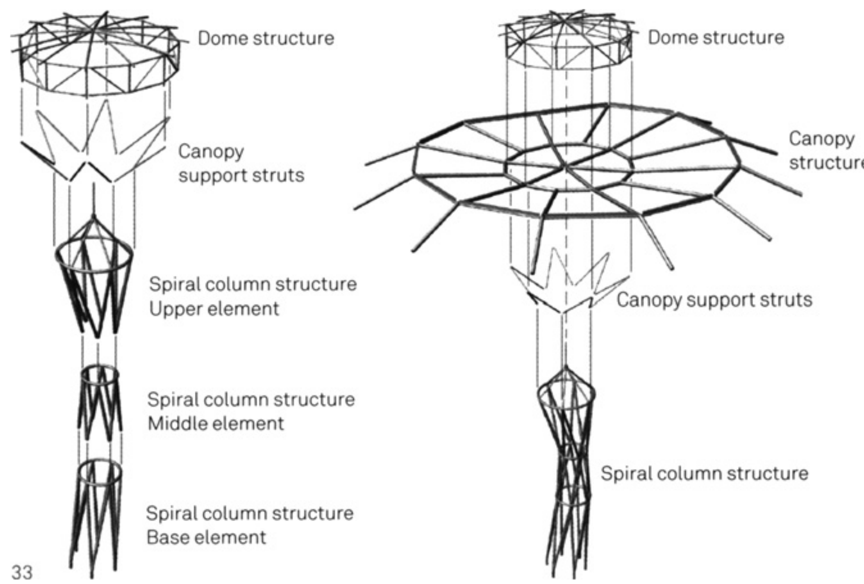

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Clarke Quay, Singapore
Alsop Architects, 2006 /
31–32__Like 19th century glazed arcades, ETFE umbrellas cover city streets. /
33__Canopy structure components /

create visual axes through the station that help to orient passengers. They ensure the continuity of the wave form across the roof and, as soft structures, contract and expand in response to changes of temperature, dynamic wind loads and significant internal air currents generated by arriving and departing trains.

The capacity of ETFE cushion systems to modify the urban environment is also explored at Clarke Quay in Singapore, completed in 2006. Clarke Quay, on the urban waterfront of the Singapore River, is located at the junction of River Valley Road and Read Street, which are lined with historic colonial terraced "shophouses" that are occupied by shops and restaurants. These streets and the square created at their intersection, formerly open air, are now sheltered by a canopy of ETFE umbrellas that protects pedestrians both from the daily deluge and the oppressive heat of the sun. The 24 meter diameter umbrellas are supported on lattice columns comprising 220 millimeter diameter steel tubes. At the top of each twisting, animated column, a triangulated collar anchors radial struts, which are suspended from cables carried by a cone of steel tubes. This radial structure is in turn braced by circumferential struts. The canopy is 18 meters high in the streets and 24 meters high in the square to assist with cross ventilation in this larger space.

Two layer ETFE cushions, printed to create a dappled pattern of light and shadow, clad the central zone of each umbrella. The pattern, derived from the leaves of the rain tree, which is common in Singapore, varies in density to produce a shading coefficient of 60 percent in the streets and 80 percent in the central square. Vertically mounted slow speed mechanical fans, which are housed in bespoke white fiberglass "whale tails" within the lattice columns, generate an artificial breeze. To ensure that this ventilation strategy works effectively, the perimeter of the open-air canopy is partially closed down by the outermost ring of each umbrella, which overhangs the existing buildings and is clad with a single skin of ETFE. Since it is not a cushion, this outer ring of cladding, like a conventional fabric membrane, is tensioned by the primary structure and by a stainless steel cable welded into the scalloped edge of the ETFE film. This thin edge detail also serves to visually lighten the appearance of the canopy. While rainwater at the perimeter is shed onto the roofs of existing buildings,

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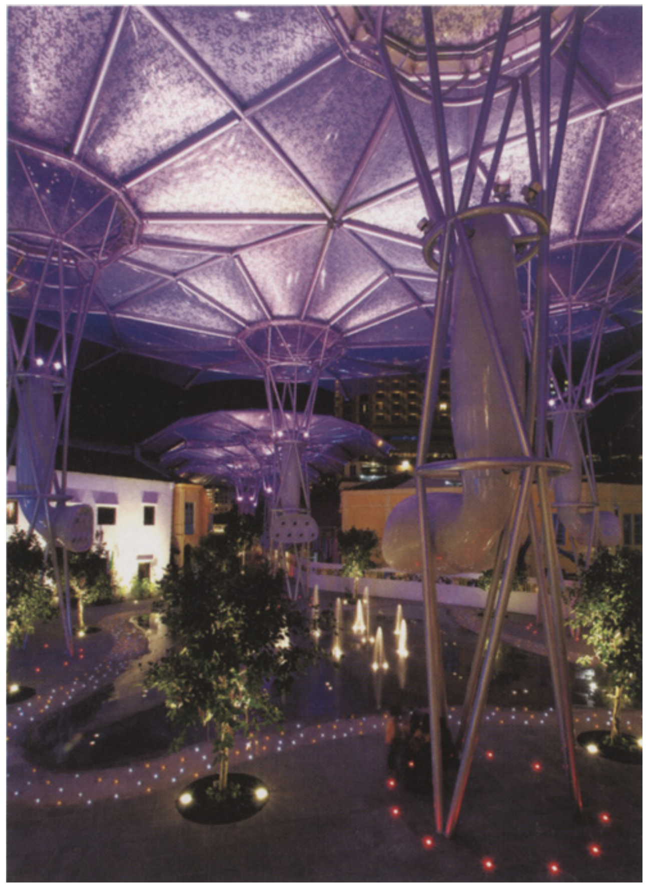

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34–35__Two layer printed ETFE cushions provide shade and protection from tropical rains, while whale tail fans housed within the lattice columns create artificial breeze. /

most of the canopy is drained by gutters between cushions, which discharge into rainwater pipes sleeved in selected tubes of the lattice columns.

Trees under the umbrellas provide additional shade and chilled water fountains in the square produce mist for evaporative cooling, which is augmented by the cool surface of the shop vitrines. The cumulative effect of these combined active and passive strategies is a temperature that is 3–5 degrees Celsius below the ambient temperature, an effect that is magnified by the psychological cooling provided by breeze and shade in this designed microclimate. Finally, programmable uplighters illuminate the canopy at night. These umbrellas, both playful and practical, have transformed an area of the city that had lost its appeal into a lively urban quarter with a comfortable outdoor environment.

Environmental manipulation

This strategy of creating an environmental umbrella is also being used at Discovery Bay School in Hong Kong. Located on the south side of Lantau Island, this private independent school for the English Schools Foundation serves 1400 children ranging from 5–19 years of age. The U-shaped building, which rises from three stories at its east end to seven floors in the west, wraps an open-air courtyard, which is the social heart of the school. Classrooms and administration are concentrated in the lower north wing of the building, while the library, theater, sports hall and pool, which are all accessible to the public outside of school hours, are located in the higher south wing. In this way, spaces that require external awareness benefit from extensive glazing on the shaded north face of the building, while the more solid south façade acts as a barrier to minimize heat gain. The building volume is sliced by cross-axial view and ventilation corridors.

Instead of the usual Hong Kong strategy of elevating schools on pilotis to create the required covered playground, the school has roof terraces on every floor, which satisfy this requirement and provide outdoor areas for informal learning and social interaction that can be accessed directly from interior spaces. The entire building is sheltered by an ETFE roof canopy, an umbrella that also draws air through the building and reduces solar heat gain. The canopy structure comprises curved steel trusses

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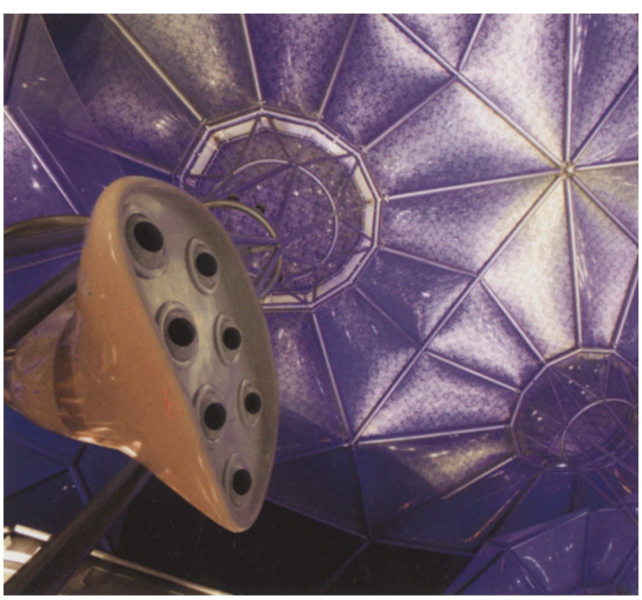

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36–37__Evaporative cooling complements shade and breeze to create a comfortable microclimate. /
38__At night, programmable lighting gives the canopy a dynamic character. /

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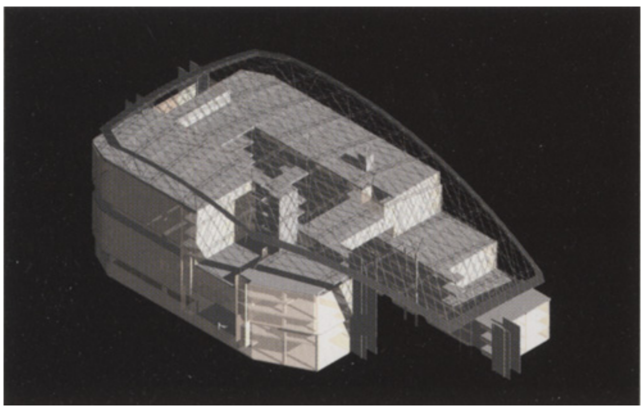

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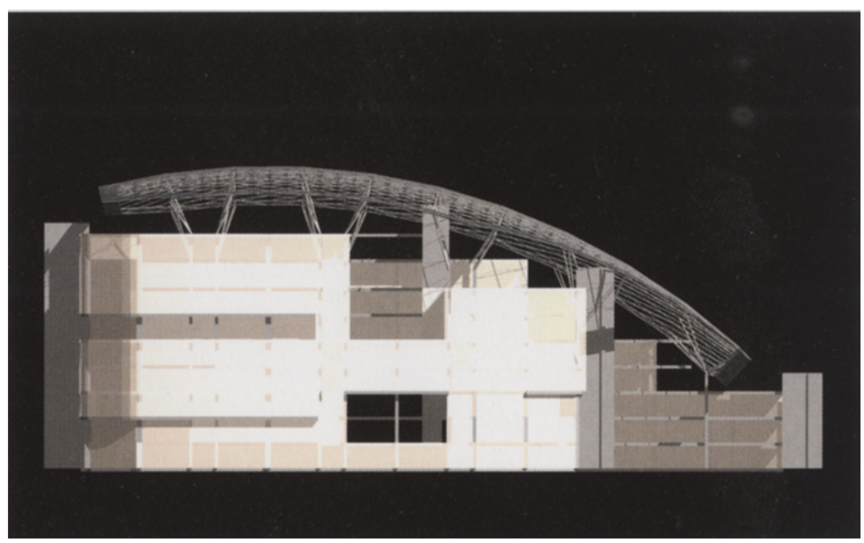

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Discovery Bay School, Hong Kong
Integrated Design Associates, 2007 /
39–41__The ETFE cushion roof canopy shades and induces natural ventilation, reducing the need for air conditioning and extending the use of the school's central courtyard and rooftop terraces. /

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Living 2000, Hanover
Willen Associates Architekten, 2000 /
42–44___This low energy housing development, which is organized around a series of microclimatic atria with ETFE cushion roofs, demonstrates the application of ETFE to a widening range of building types. /

45

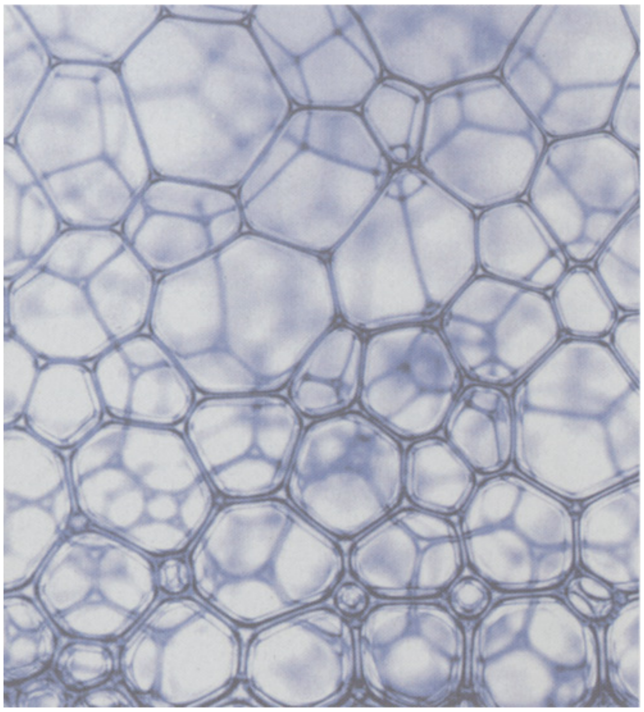
National Aquatics Center, Beijing
PTW (Australia) + CSCEC Shenzhen Design Institute (CSCEC + Design), 2008 /
45__The Water Cube is inspired by the image of water and, in a city where the resource is scarce, aims for a high level of sustainable environmental performance. /

supported by tree-like steel struts that extend from concrete columns along the north and south faces of the building. Above the terraces, the outermost layer of foil is printed to provide solar shading, while above the central court, all three layers of foil are clear to ensure as much daylight as possible reaches inward facing classrooms on lower floors. Following the profile of the building, the canopy dips down to shield the courtyard from east winds and rises to the west to aid ventilation. Through the stack effect, cool air in the shaded central court is drawn up to temper the outdoor covered areas. This cool air also enters the building through opening windows on the courtyard façades and is exhausted on the external faces of the building. The printed areas of the canopy shade the open-air swimming pool and terraces on the building's roof, projecting temperatures up to 6 degrees Celsius lower than if there were no canopy. In Hong Kong's hot and humid climate, this cool, breezy and shaded microclimate greatly enhances thermal comfort, both actual and perceived. In addition to reducing reliance on mechanical cooling for the interior spaces, the ETFE canopy significantly extends the hours of both daily and seasonal use of the covered outdoor court and terraces.

Olympic gold

The National Aquatics Center in Beijing has been designed to maximize the performance of the building envelope and, like the Eden Project, is another of the new generation of buildings designed specifically for an ETFE cushion system. Nicknamed the "Water Cube," this building for the 2008 Olympics has a two-way clear span of 177 meters. The tubular steel structure is inspired by the geometry of a continuous array of bubbles. Using images of sea foam, engineers at Arup based the structural design on the work on soap bubbles started by physicists Plateau and Kelvin in the 19th century and concluding with the geometry defined by Irish professors Weaire and Phelan a century later.

The resulting structure is a repetitive system comprising 22,000 tubular steel beams and 12,000 nodes, which are subject to 190 different loading conditions. The irregular space frame is a totally welded structure of steel tubes ranging from 168–610 millimeters in diameter. The sizing of the compact sections, together with the specification of ductile steel, enables plastic deformation to address the significant seismic requirements of construction in this region. Modules of the space frame were site welded to form



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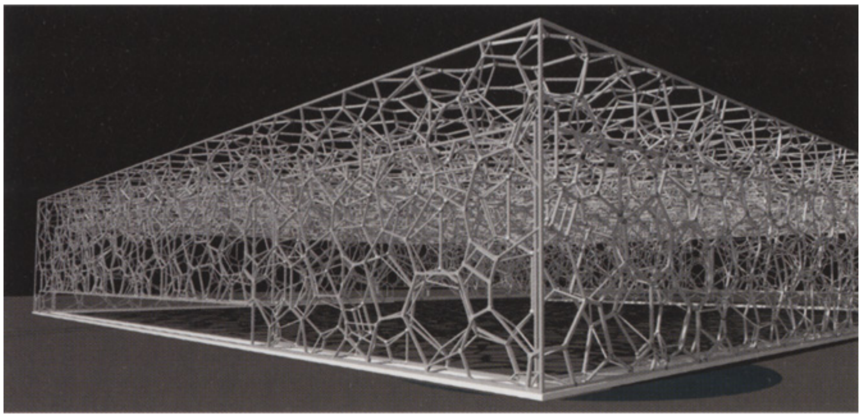

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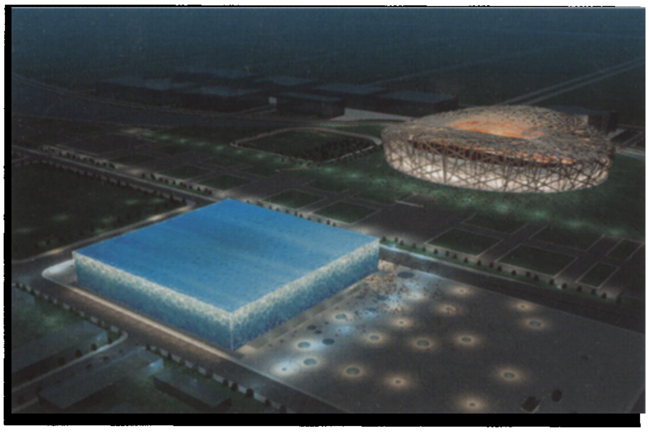
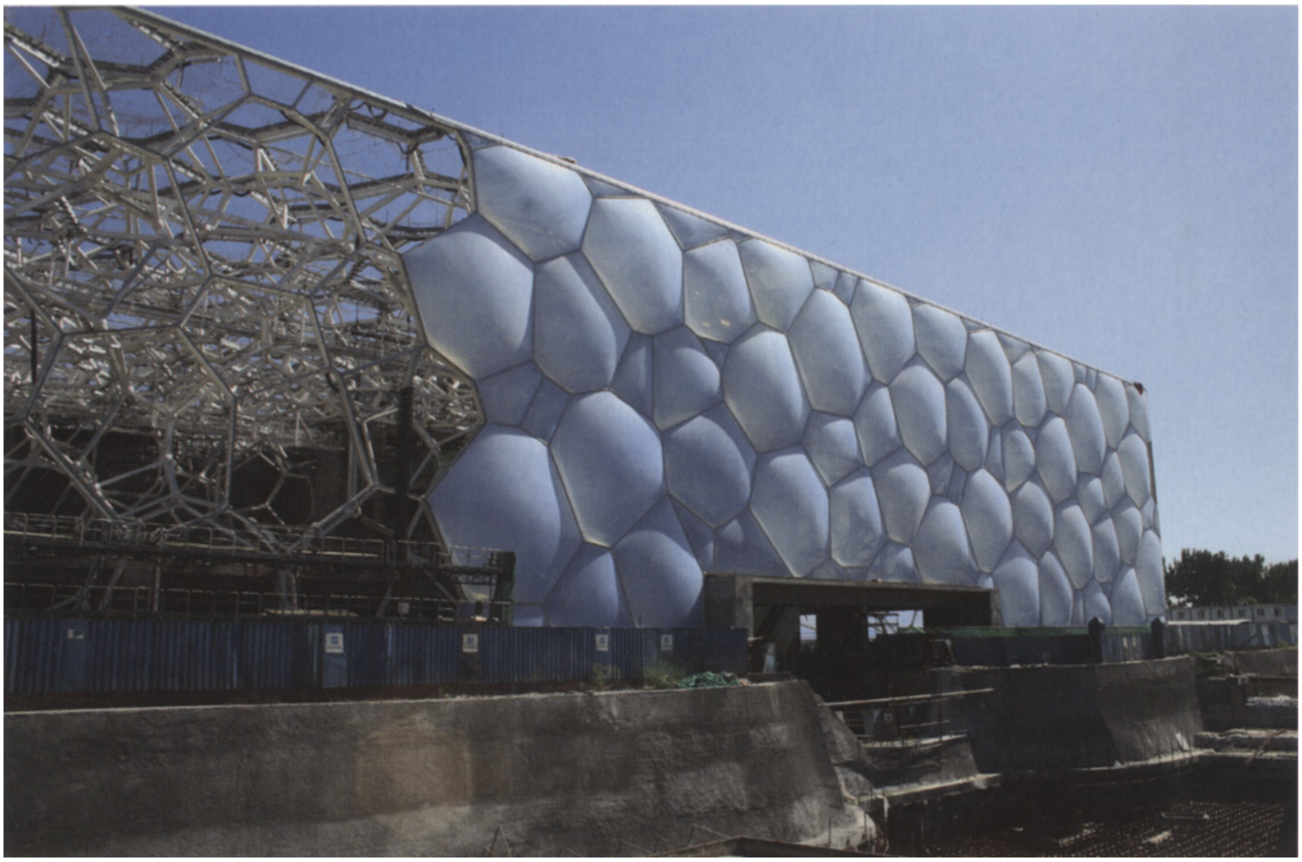


46–49__The building's structure, derived from an array of bubbles, is a repetitive space frame comprising irregular polyhedrons. /



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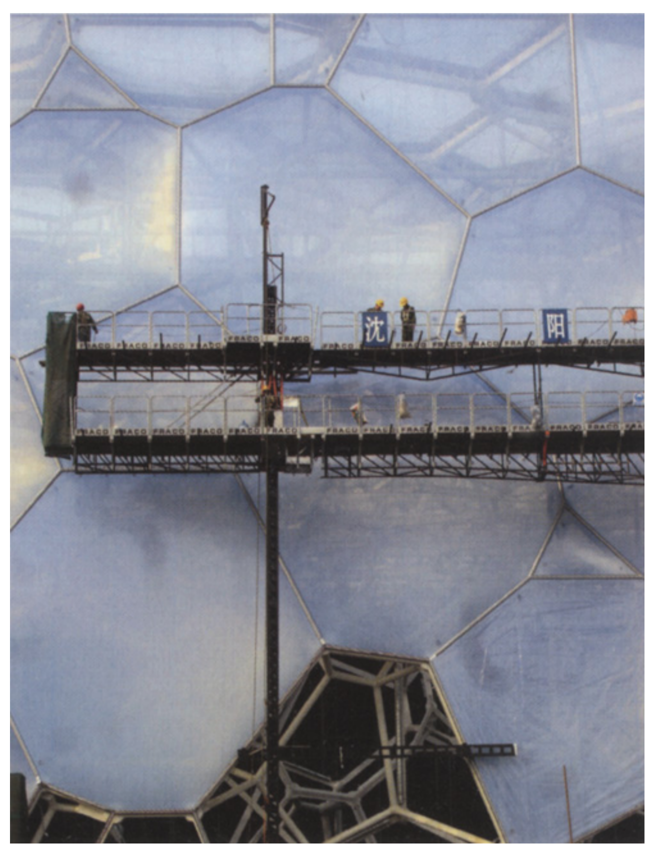

50–51__The bubbled wall surface comprises 13 cushion shapes that repeat on a 20 x 40 m module. The ETFE cushion envelope enables the building to be daylit, induces natural ventilation and, in winter, captures solar heat for the thermal mass of both water and concrete. /


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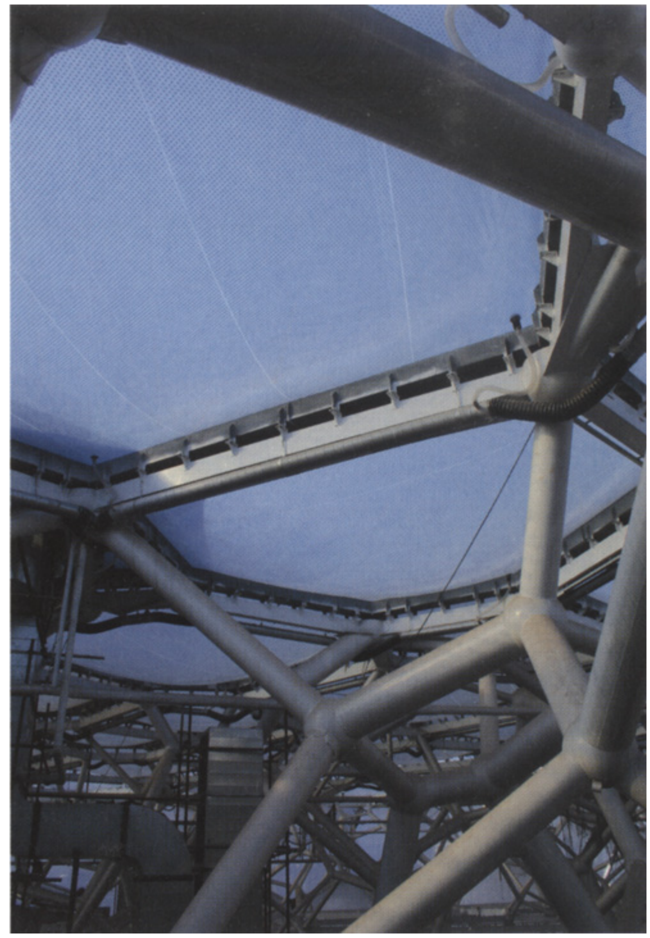
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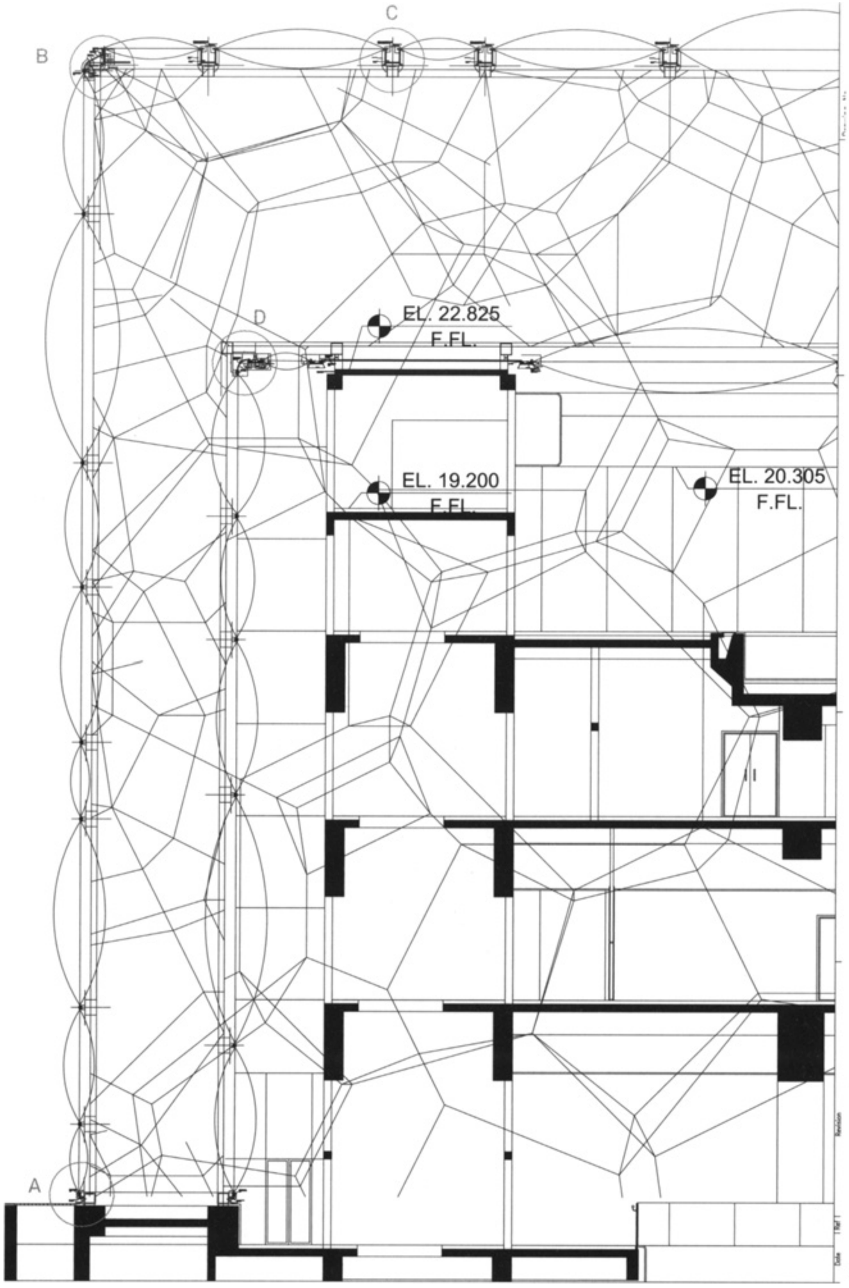
52–54__Each of the 3500 cushions is unique and custom engineered for the conditions in its particular location on the building's surface. Cushion variables include shape orientation, number of foils, foil thicknesses and colors, percentage of pattern and seam distribution. /

3.6 meter thick walls and a 7.2 meter thick roof, which are both clad with two discrete ETFE cushion envelopes on the inner and outer faces, using three layer cushions on the walls and four layers for the roof. This double skin veils the structure and, with six to eight layers of foil in total, provides excellent thermal insulation. U-values better than 0.6 $Wm^{-2}K$ are being achieved, which are further reduced to approximately 0.35 $Wm^{-2}K$ once solar gains and heat losses due to infiltration are considered. The Water Cube uses nearly 100 metric tonnes of ETFE foil, over three times the amount used for the Eden Project.

To achieve the foam pattern in the building's skin, there are 13 primary cushion shapes for the façade and seven for the roof, which combine to create a mosaic that repeats on a 20 x 40 meter module. Further shapes result when these are truncated at the edges of the building. Other variables include shape orientation, number of foils per cushion, foil color and thicknesses, and percentage of printing and weld seam distribution. Seams are laid out to ensure a continuous 1.5 meter grid, which is vertical on the walls and free form on the roof. The camber of all cushions is 15 percent, higher than usual, both for visual reasons to emphasize the bubbled surface and for structural reasons, as the stress of the material is dependent on camber. Ranging in size from 1 x 2 meters to approximately 8 x 11 meters, each cushion is custom designed to deal with the particular stresses and conditions in its location on the building's surface. Consequently, each of the 3500 cushions is unique. The building's color is derived from the outermost layer of foil, which is body tinted blue, while all other layers are either clear or printed. Density of the silver dot pattern relates to orientation, ranging from 10–60 percent to provide varying levels of solar shading. Pattern distribution is also in part aesthetically determined, with the envelope designed to be more transparent at corners and edges – for example at the junction of wall and roof – so that the structure may be seen through the cushions.

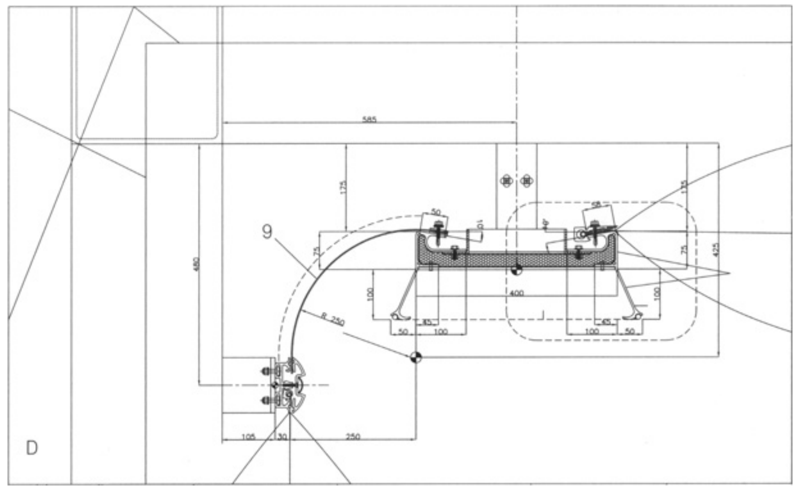
While the envelope of the Water Cube has undoubtedly been conceived with the image of water in mind, it also aims for a high level of environmental performance. In this densely populated city where water is a precious and unreliable commodity, the building is designed to harvest all of the pool backwash, which is recycled, and 80 percent of the rainwater from the roof and surrounding site, which



is to be used as graywater. Because of its transparency, this vast building can be largely naturally lit, potentially reducing artificial lighting costs by half. The cushions also act as acoustic absorbers, which is a significant benefit for the noisy environment of indoor pools.

Further, the double skin, with its low embodied energy, was conceived as a thermal duvet, which transforms the building into an enormous greenhouse that can use the sun to passively heat both building and pool water, resulting in a projected 30 percent saving on the typically high heating costs of indoor aquatic centers. The double façade has three seasonal modes of operation. During temperate mid-season, opening vents in both skins naturally draw air through the building. Fresh external air is admitted through the outer skin, preheated by the sun in the cavity between skins, and then supplied to the pool areas. During summer, when external conditions are hot and humid, the internal skin is sealed. Air cooled by passing over water around the building's perimeter enters the cavity through a 1 meter high bank of vents at grade, heats up, rises and is exhausted by roof vents. In winter, both skins are sealed to achieve zero heat loss through infiltration and maximize thermal performance. To reduce diurnal and seasonal temperature swings, the thermal mass of the pool water and the concrete pool and stadium structures are utilized to absorb the sun's heat during the day and re-radiate it at night. The external water, like the skin itself, plays a number of roles. In addition to providing evaporative cooling, the water is a security moat to prevent vandalism of low level ETFE cushions and a reflecting pool that enhances the presence of the building, particularly when lit at night.

Multiple safety measures are incorporated to prevent ponding on this expansive flat roof. Each cushion is surrounded by a siphonically drained gutter, which incorporates outlets at 20 meter centers. Instead of the typical detail of one air supply per cushion with a small pressure equalization hole in each of the inner foil layers, the cushions have two inflation systems to ensure that the middle air cavity remains at a higher pressure than the outer cavities and that the cushions remain inflated should one supply fail. Inflation fans also have a backup electrical supply. Air feed valves are small in diameter so that if there is a failure in one cushion, the whole system still maintains pressure. As on the Eden Project, some roof cushions with



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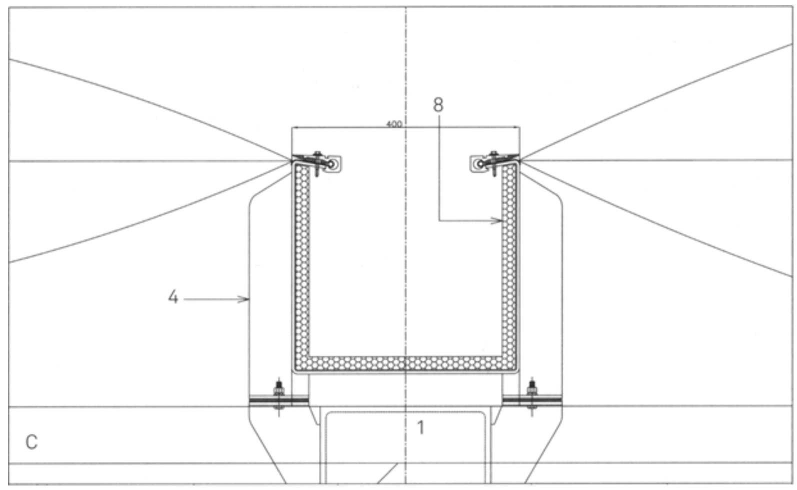

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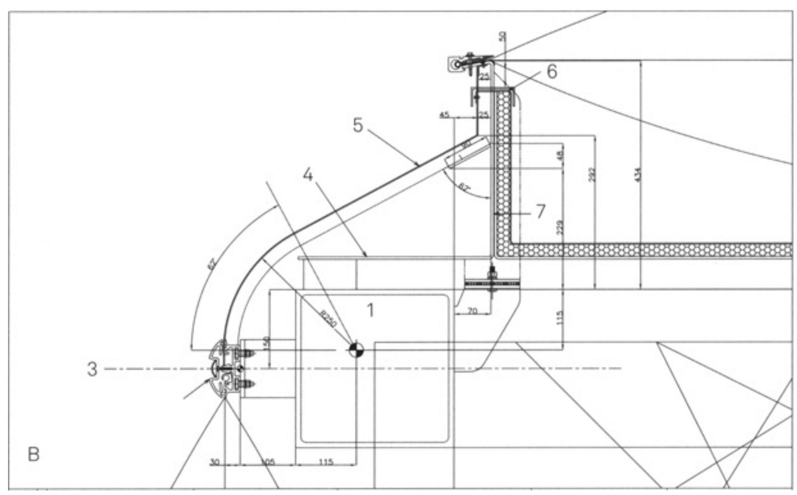

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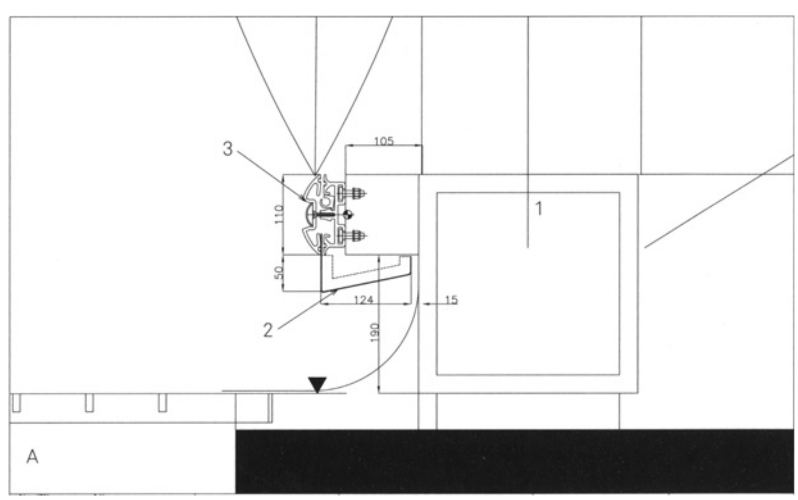

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55__To achieve a 177 m clear span, prefabricated modules of steel tubes are site welded to form 3.6 m thick walls and a 7.2 m thick roof. Walls and roof are clad with two separate ETFE cushion envelopes on the inner and outer faces. /
56__Internal skin wall to roof detail /
57__External skin roof detail /
58__External skin wall to roof detail /
59__External skin at ground
1 main steel structure
2 20 mm drain hole at 1 m centers
3 extrusion, waterproofed between caps
4 steel bracket
5 insulated aluminium flashing
6 PVC under alloy
7 steel gutter section
8 PVC gutter lining
9 insulated aluminium flashing with integral vapor barrier /

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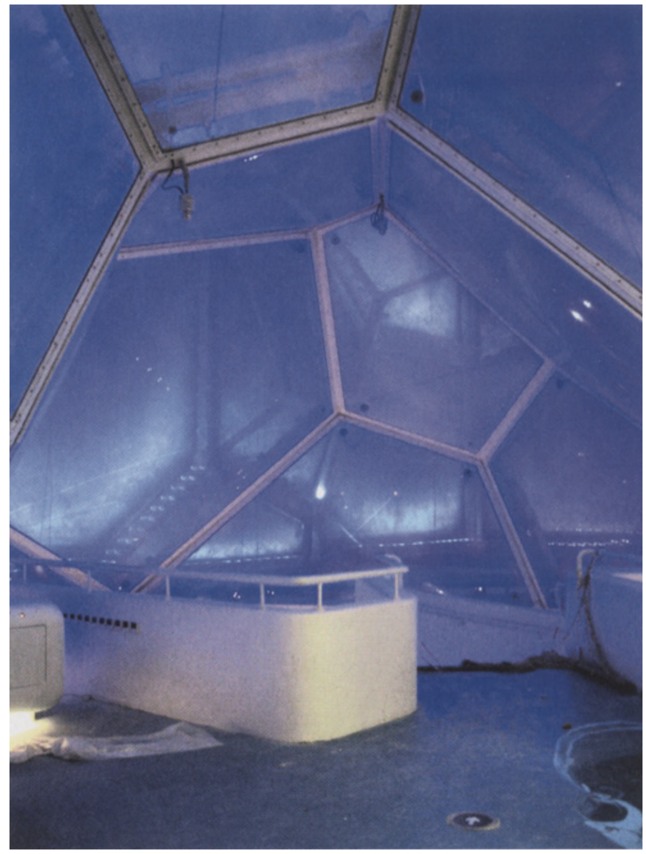

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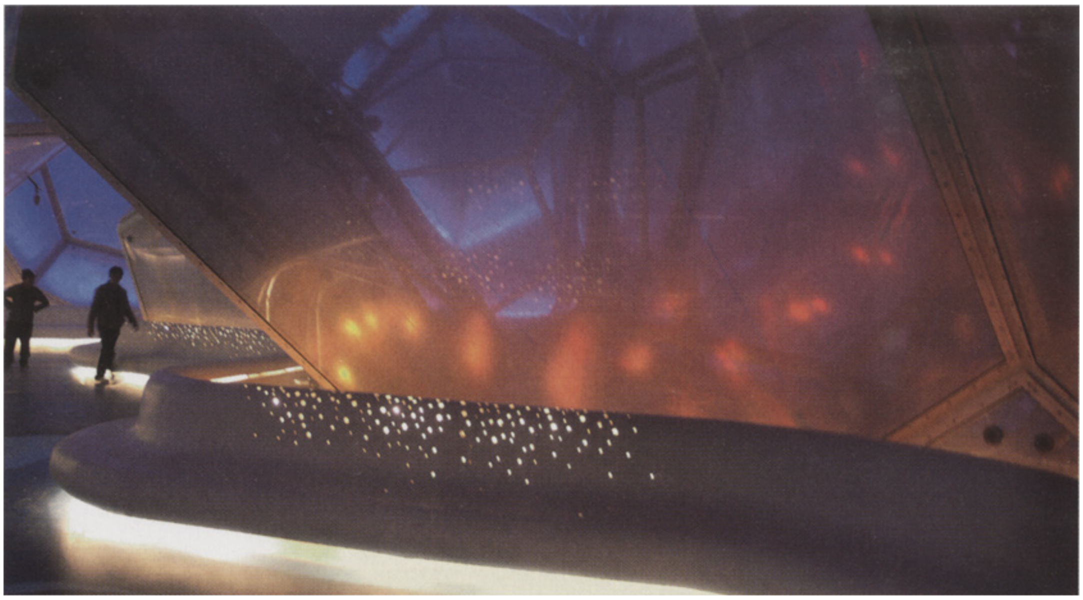
60__At the building's edges, the structure is visible through the translucent ETFE envelope. /
61–63__Interior views /

potentially high stresses have load sharing foils on the outermost layer. Finally, should the top layer of roof cushions invert under ponding conditions, all layers are designed to work in tension and engineered to withstand the imposed loads. When inverted, all layers of foil act together, effectively load sharing to make a very strong membrane.

The ETFE cushions were fabricated by Vector Foiltec in Beijing, and site installation by local laborers, who were specially trained to work with foil, proceeded rapidly at a rate of 1500 square meters per day. The cost of this envelope system, with its large ETFE cushion components and lightweight steel structure, is half that of a typical double glazed envelope and achieves U-values better than two layers of triple glazing.

With multiple performative attributes, the low energy, naturally engineered environments of ETFE cushion enclosure systems are being acknowledged for the positive ways in which they address many of the increasingly significant issues of energy consumption and sustainability in the built environment. The preoccupations of Buckminster Fuller and Frei Otto with lightness and building in harmony with nature are compelling concepts. Advances in material science and in the design of high performance building envelopes, as represented by ETFE cushion systems, are making it increasingly likely that these utopian visions can be realized.

1__This phrase is from Ron Witte's essay "Substance," *immaterial/ ultramaterial* (Harvard Design School and George Braziller, 2002), in which it is used to describe aerogel, a silica-based substance that is made up largely of air.
2__1.5–3 percent of light cannot pass through the material in a straight line.
3__Texlon Optic (high optical transparency ETFE foil) is a patented product of Vector Foiltec.
4__Texlon HH (Helmholtz absorption system) is a patented product of Vector Foiltec.
5__Texlon RS (rain suppression system) is a patented product of Vector Foiltec.
6__Rebecca Roke. "Southern Skies," *The Architectural Review* (February 2007) p. 58.



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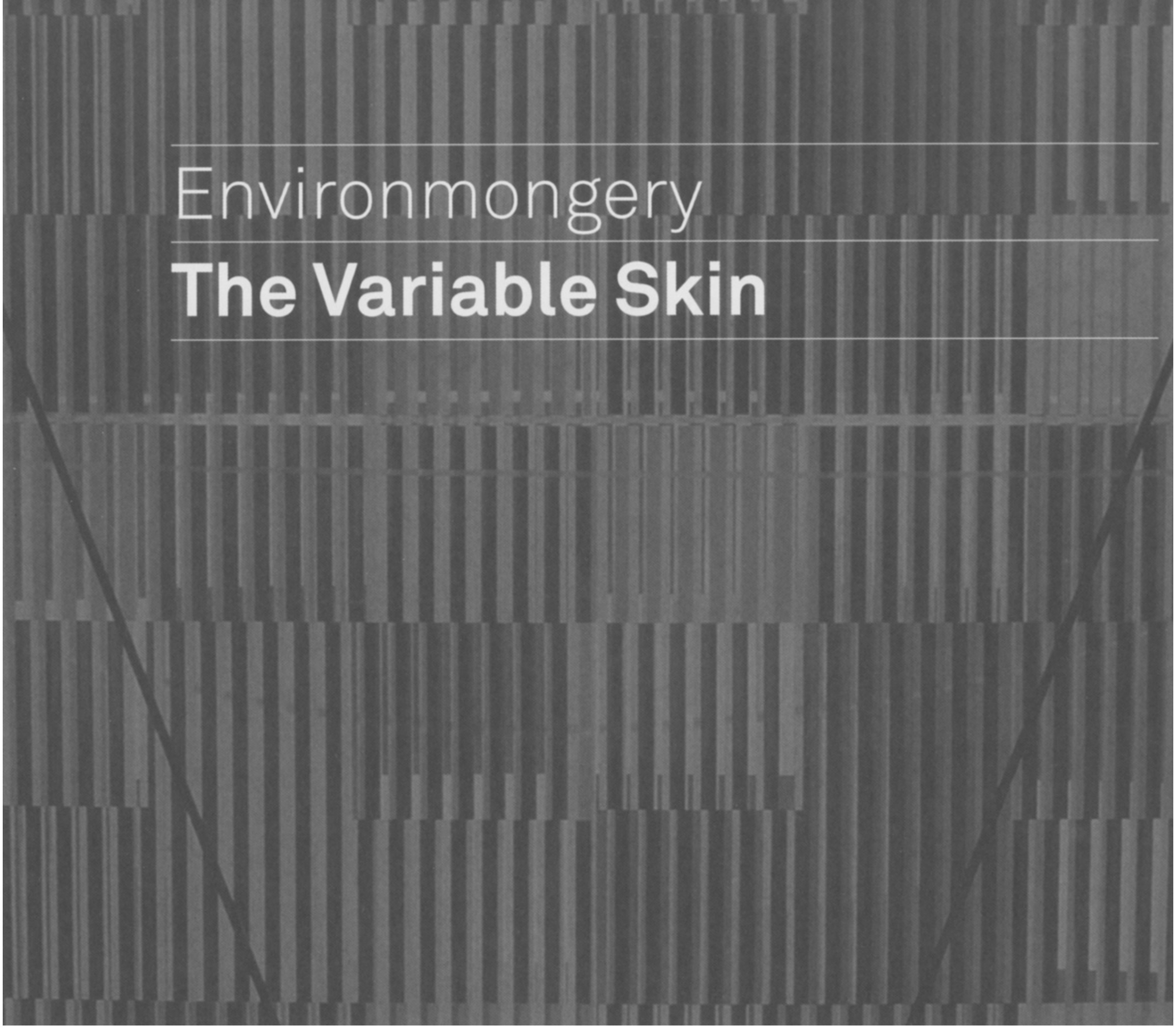
Environmongery
The Variable Skin

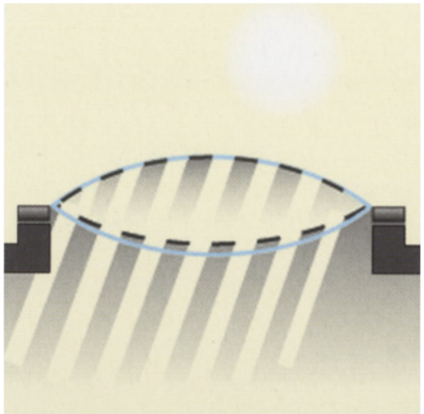


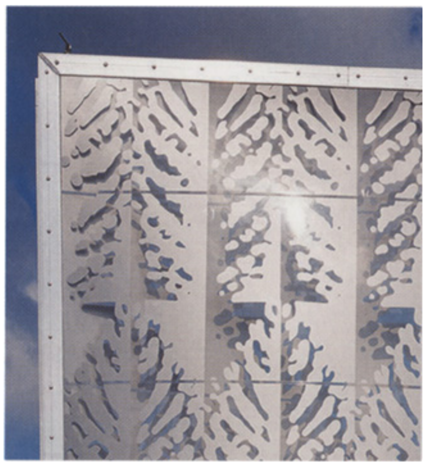
For ETFE cushion systems, the variables that are determined at the design stage – including the number of foil layers, their pigmentation and printed patterns – enable designers to finely tune building envelopes to their environments. In addition, this technology allows building envelopes to be dynamic. Current developments are the result of two strategies that may be used separately or in tandem: the introduction of variable air pressure within the cushions to augment their environmental responsiveness and the addition of other technologies to cushion surfaces to broaden the scope of their performative attributes.

Services as software

The term "environmongery," used in the "Pneu World" issue of *Architectural Design* in 1968 to describe the work of Nikolaus Laing, suggested that the software of air pressure has great potential to replace the hardware of mechanical systems. Laing's early experiments with pneumatically operated membranes are now being realized in ETFE cushion envelopes. Simply by varying the air pressure between cavities, ETFE foil layers can be moved toward or away from each other. By introducing a separate air supply to each cavity in the cushion, the volume and number of air cavities can be changed to alter the thermal performance of the envelope. Even when using transparent foils for all layers, the greater the number of cavities, the better the thermal performance. Further, the ability to incorporate different printed patterns on the foils, which can be overlaid or moved apart by dynamic air pressure, alters both the daylight transmission properties of the envelope and its visual appearance.

The first variable ETFE envelope was the temporary Cyclebowl in Hanover for DSD Duales System at the 2000 Hanover Expo. Duales System, which manages Germany's garbage separation and recycling, opted for ETFE because of its compatibility with the environmental preoccupations of the company's business. The pavilion, which demonstrated a range of passive environmental strategies, was teacup-shaped in section with an exhibition about recycling organized along a spiral ramp at the perimeter. It featured an ETFE roof and walls, both made of three layer cushions with the outer two layers printed with leaf patterns. As part of the exhibition, the middle foil of the cushions was programmed to open and close at intervals to





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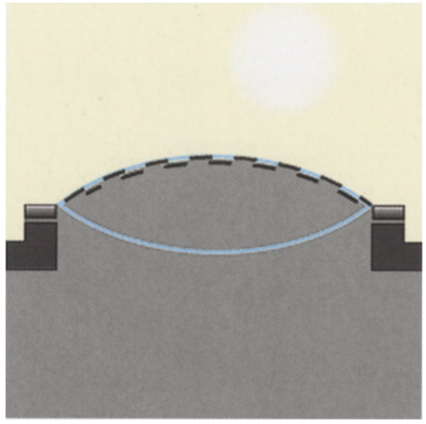

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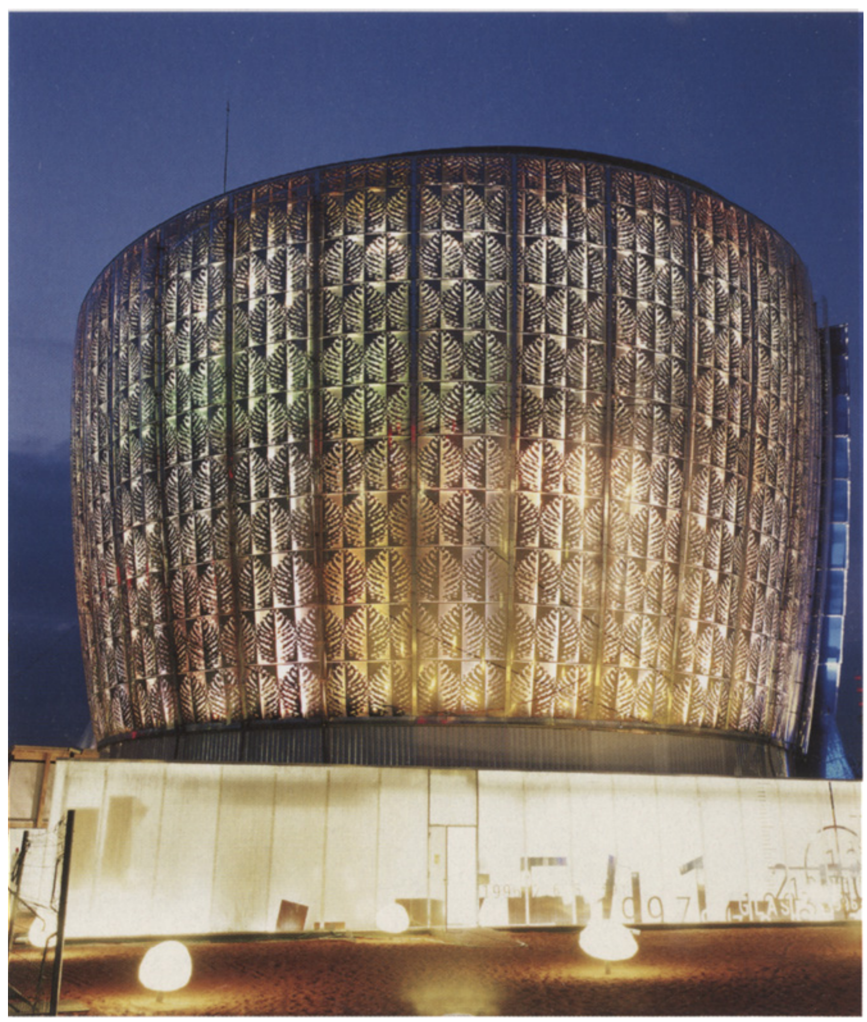

Cyclebowl, Hanover
Atelier Brückner, 2000 /
1–4__With patterned cushions of three or more foils, variable air pressure moves the middle foil to manipulate the insulation value and shading coefficient of the envelope. Pattern open (1–2), pattern closed/superimposed (3–4) /
5__A temporary pavilion at Expo 2000 in Hanover for DSD Duales System, a company involved in sustainable practices, was the first application of a variable ETFE cushion envelope. /

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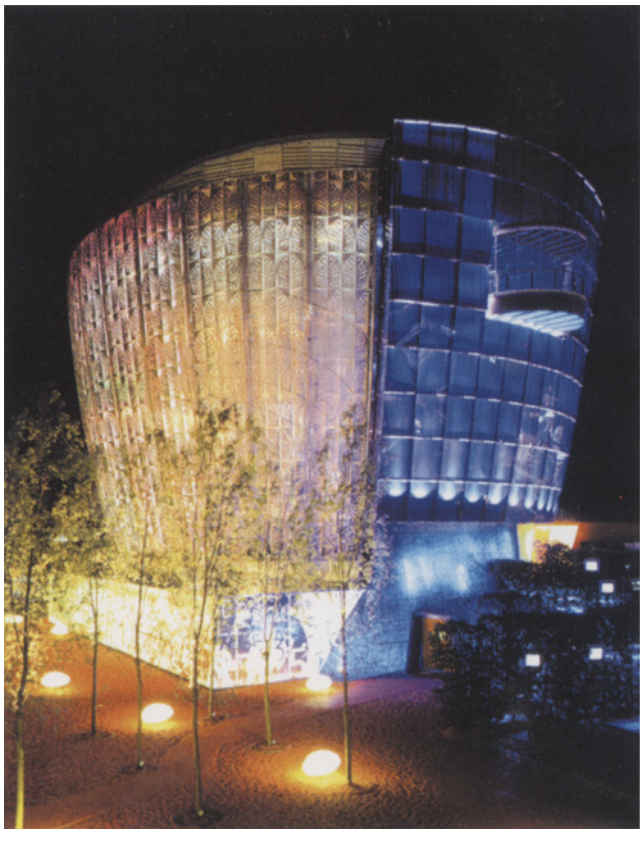

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6–8__Roof and walls, both printed with a leaf pattern, were opened and closed as part of the exhibition to demonstrate the potential of the variable envelope. /
9–12__A spiral ramp structured both the pavilion and its exhibition. The roof cushion was supported by a double cable net. /


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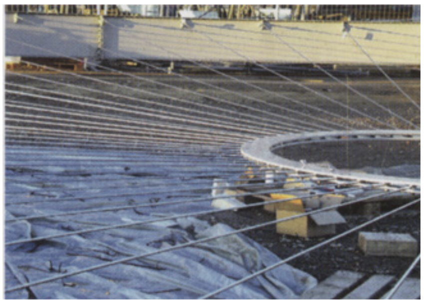
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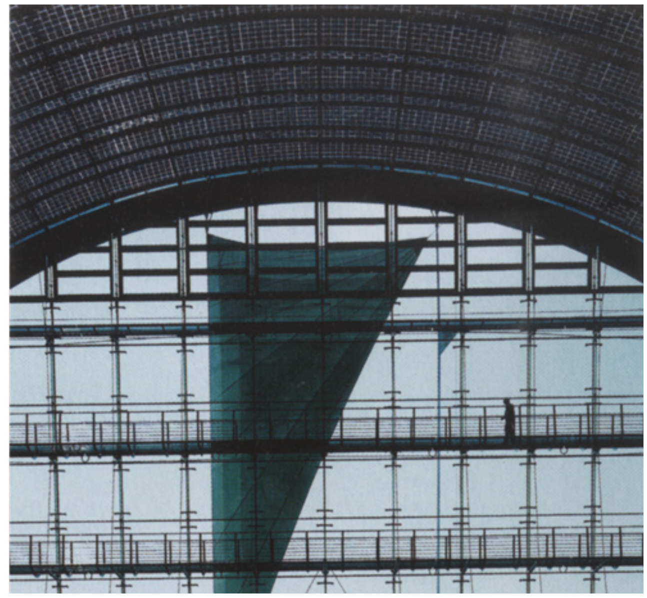

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Festo Technology Center, Esslingen
Jaschek und Partner, 2000 /
13–15__To complement its manufacture of a wide range of pneumatic products, Festo is incorporating variable ETFE cushion envelopes in its premises throughout Europe. /

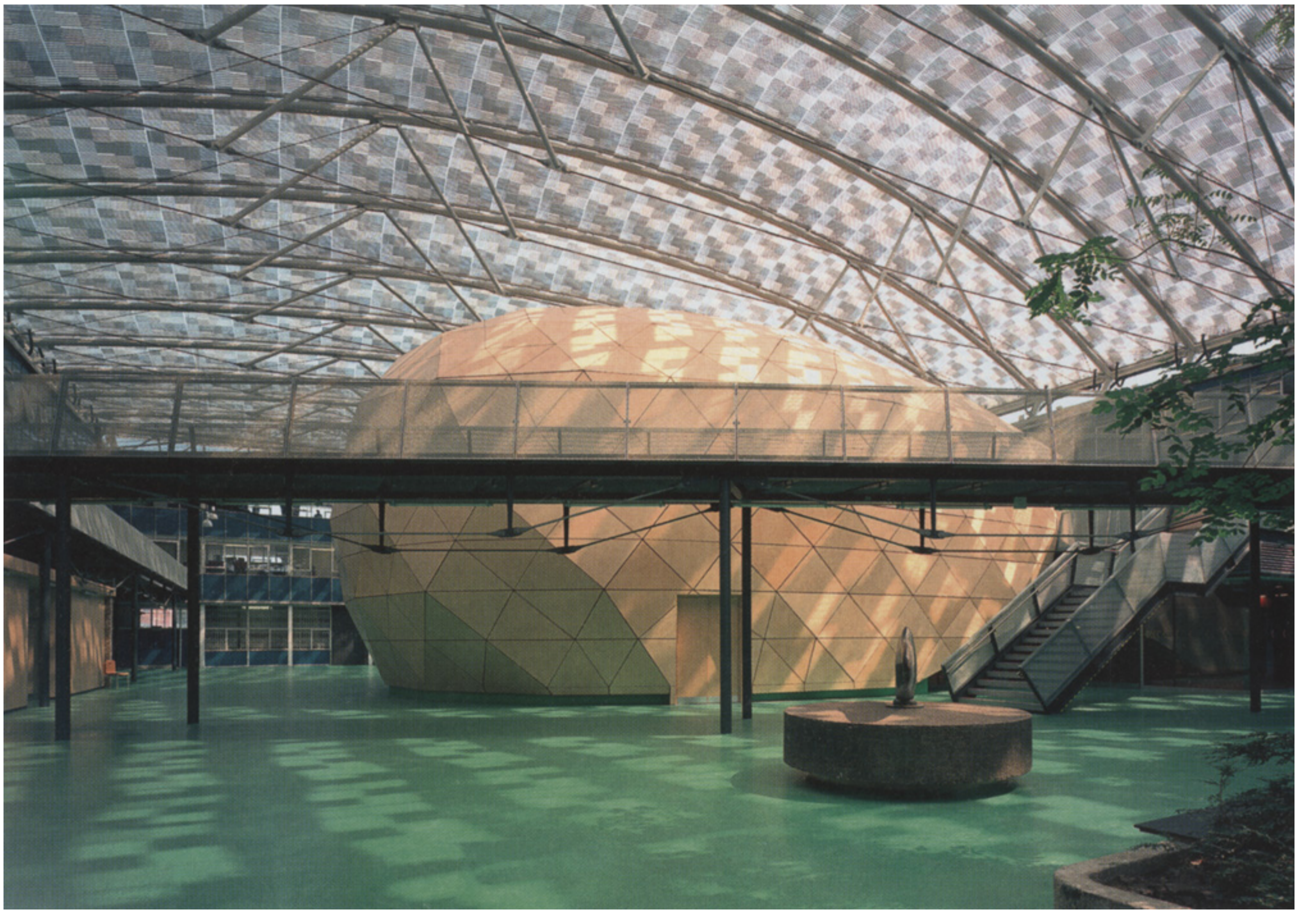
provide both a daylit interior and a darkened environment for light shows. The slightly sloped roof was a single 36 meter diameter cushion supported by internal and external cable nets. To demonstrate the stack effect, this roof supported a large fan inserted in a tube at the center, which generated a visible "twister" of smoke within the space. In addition, the pavilion was passively cooled by the evaporation of graywater, which was sprayed on the ETFE façade.

The first long-life commercial application of a variable ETFE envelope was by Festo, a company that specializes in pneumatic robotics for manufacturing, and which also makes the pneumatic cylinders that are typically used to activate opening ETFE cushion vents, as well as a range of inflatable buildings and products. Festo has adopted ETFE as part of its corporate identity and, since 2000, has constructed variable ETFE atrium roofs and skylights at its office premises in Germany, France and Hungary. Festo Technology Center in Esslingen for example has three atria with three layer printed and variable ETFE cushion roofs that provide a controllable range of interior daylight conditions.

Variable air pressure and printed patterns

The first variable ETFE skin in the United Kingdom was at Kingsdale School in London and was completed in 2004. When Labour came to power in 1997, the government set out to improve education. At the time, Kingsdale School, a state comprehensive in South London, was a troubled school on the list of low academic achievers and housed in a mid-20th century modern building that was run-down and outdated. As a result, Kingsdale was targeted by the government for investment in facilities and technology.

The first phase of work ingeniously doubled the area of the building and created a much needed social center for the school. The existing building had a figure-of-eight plan with two open courtyards. The middle bar of the plan has been removed, and the previously unused courtyards have been united to create a single large space, which is enclosed by an ETFE cushion roof. This covered court accommodates the school's social and communal functions including the canteen and a new free-standing auditorium that is elevated with the library tucked underneath. It also serves as a flexible space for performances and assemblies of the entire student body. Existing trees,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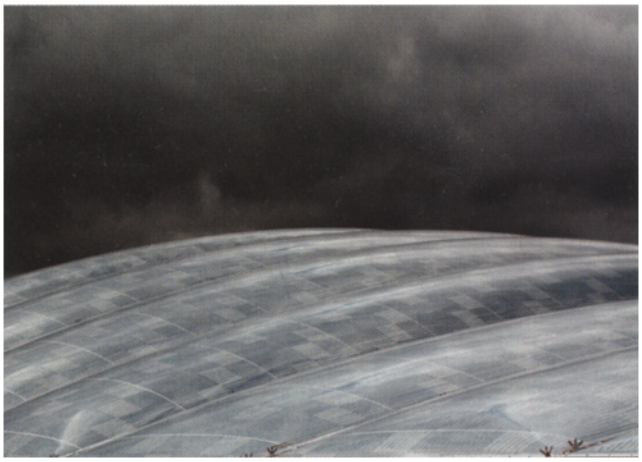
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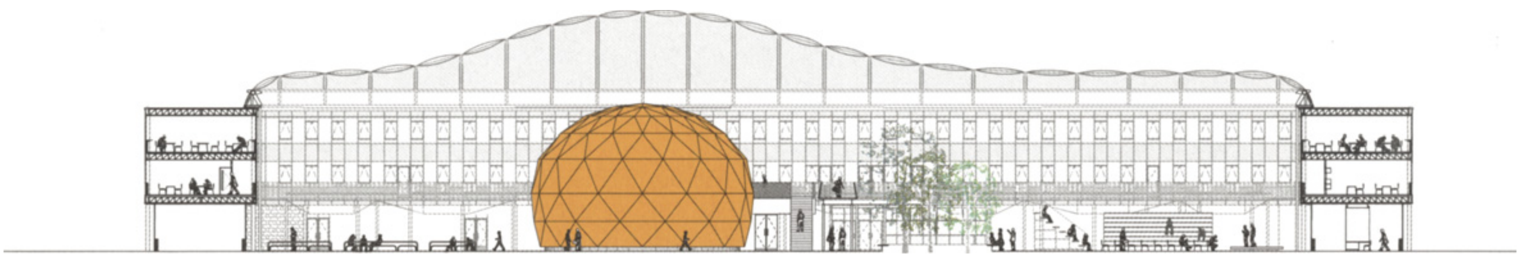
Kingsdale School, Dulwich, London
de Rijke Marsh Morgan Architects, 2004 /
16__Former unused courtyards, now enclosed by an ETFE cushion roof, house the school's social and communal functions. /
17–18__The asymmetrical hump of the roof serves as a smoke reservoir and creates space for the figural auditorium and library. /



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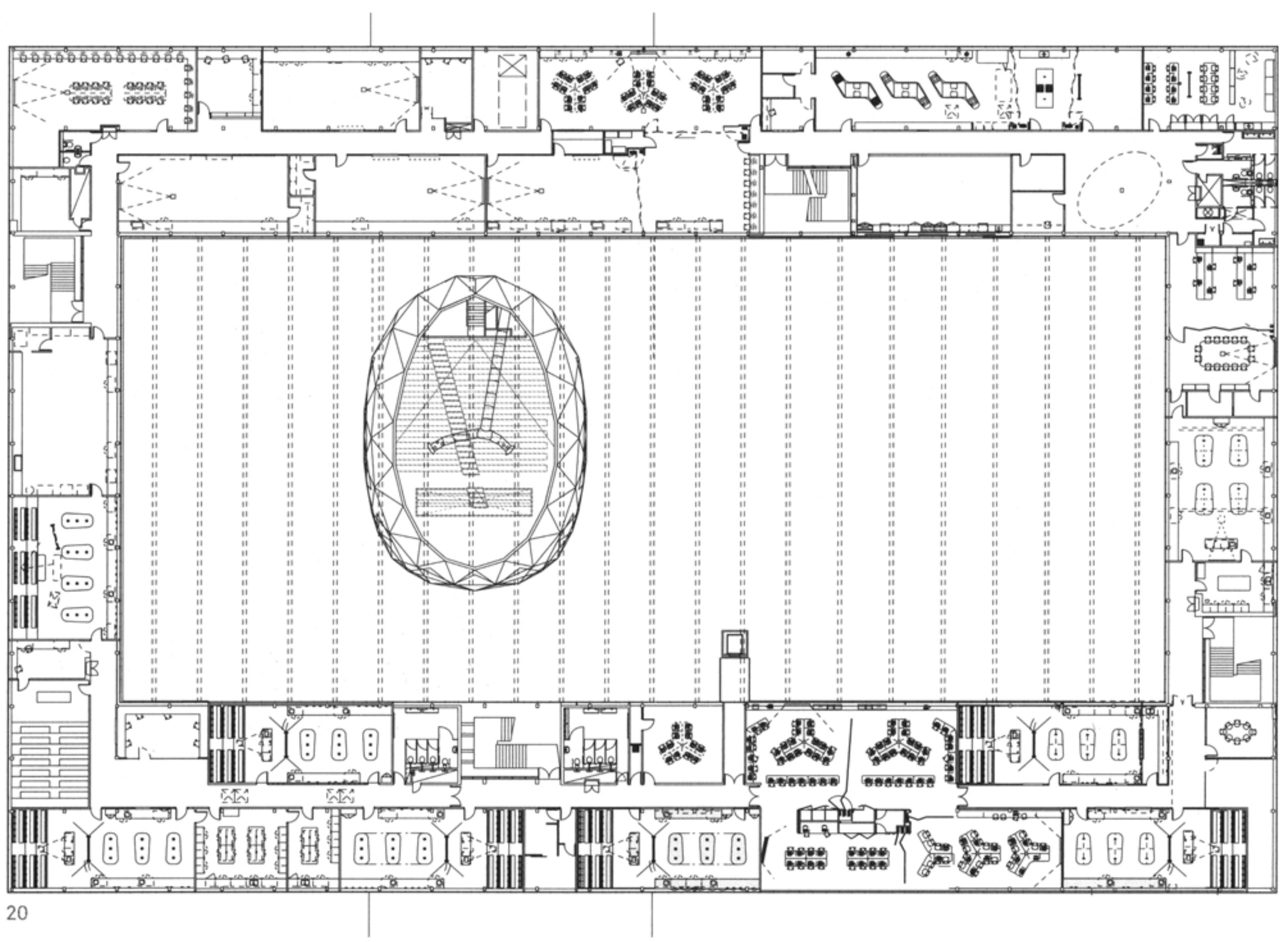

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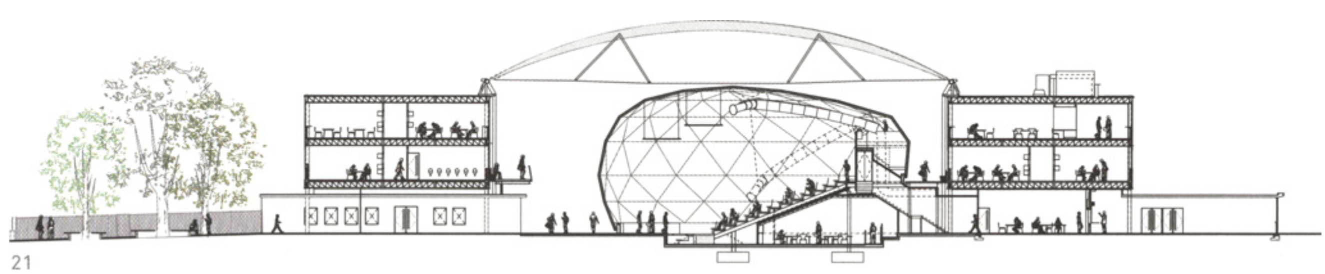

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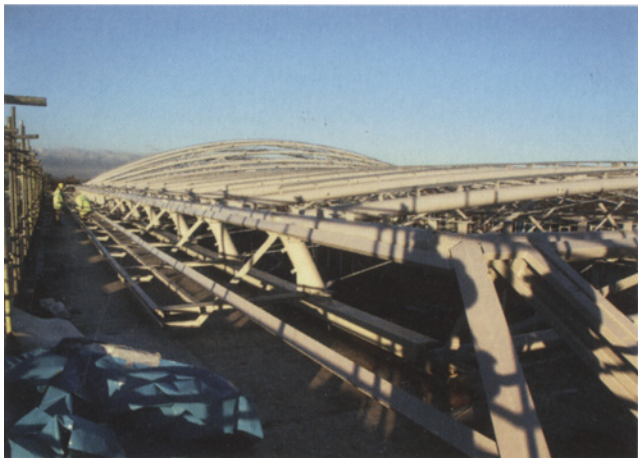
19–21_Longitudinal section, plan and cross section /



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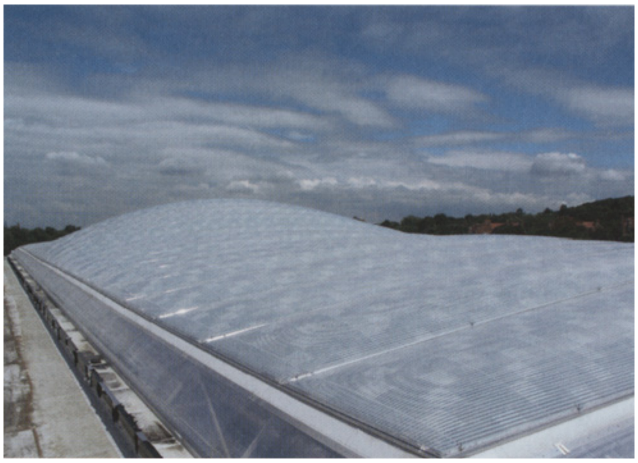

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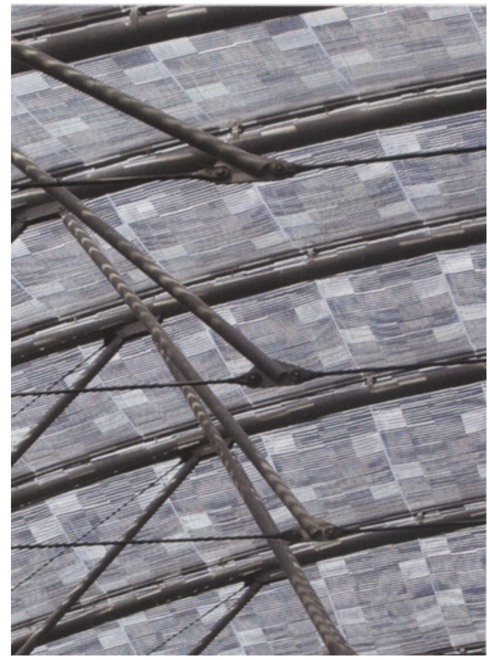

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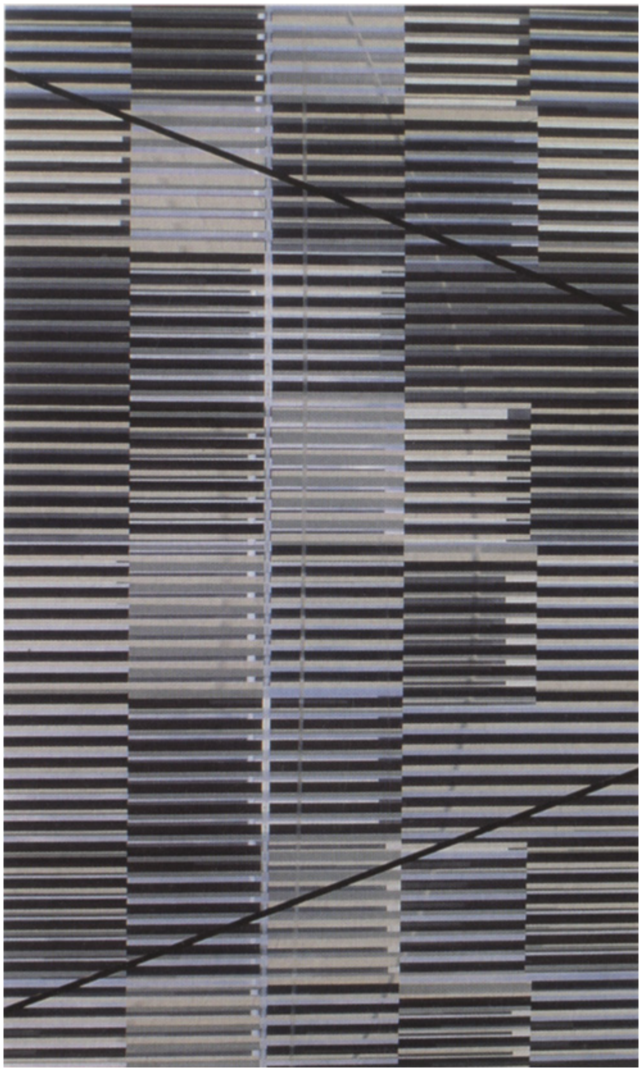
22–25__A prismatic truss reconciles the different structural rhythms of the existing building and the new roof. /

formerly outdoors, have been retained. The original double loaded corridor has been removed where possible, or reduced and opened up by vision panels in walls and doors, which allow views into the central court. A band of circulation has been added at second floor on the two long sides of the court, and a new bridge traverses the space, providing a shortcut in the circulation loop.

To liberate the ETFE roof from the repetitive module of the original building, the cross section varies along the length of the space, rising above the auditorium to form an asymmetrical hump, which serves as a smoke reservoir in the event of fire. The structural bays of the atrium roof vary from 3.5–4 meters in width, becoming narrower to deal smoothly with zones of more pronounced curvature. Bowstring trusses with top chords of 196 millimeter diameter steel tubes span 36 meters onto a prismatic steel truss. Mediating between the variable grid and the regular structural module of the original building, this ring beam deals with all horizontal forces and transfers the load of the new lightweight roof entirely onto existing columns and foundations, a strategy that resulted in considerable cost savings.

Each structural bay is enclosed with a single 38 meter long ETFE cushion comprising printed outer and middle layers with a clear inner foil. Taking a cue from the variable structural grid and inspired by the work of artist Bridget Riley, the design team developed a variable pattern similar to a bar code. Each layer is printed with its own pattern of silver FEP (fluorinated ethylene-propylene) inks, which repeats on a 1510 x 1260 millimeter module, dimensions determined respectively by the manufacturing width of ETFE foil and the maximum diameter of a printing roller. A 15 millimeter clear margin on all four sides accommodates weld seams that run across the cushions and, in the longitudinal direction, creates gaps between roller repeats. Each of the two compartments of the cushions has its own air supply, which is governed by thermostatic controls to produce differential pressure that moves the position of the middle foil. The roof allows 50 percent light transmission when the printed foils are held apart and only 5 percent transmission when superimposed. In addition to working environmentally, the different patterns on the two inner layers of foil are designed to produce a Moiré effect that constantly changes, creating a dappled and



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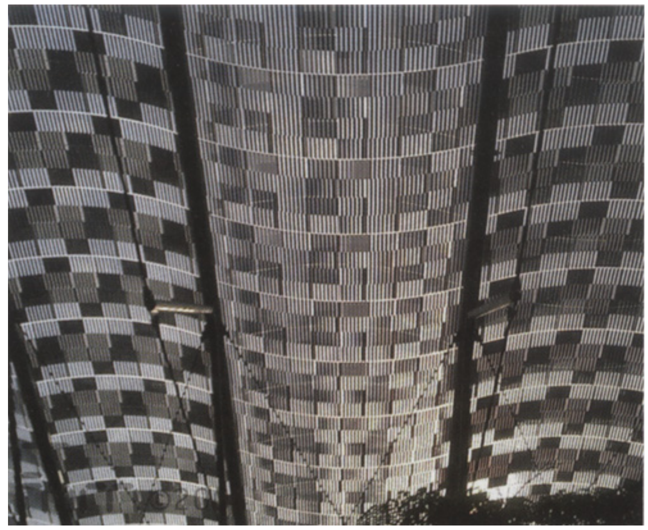

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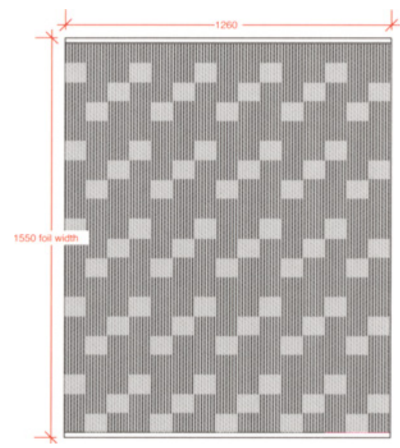

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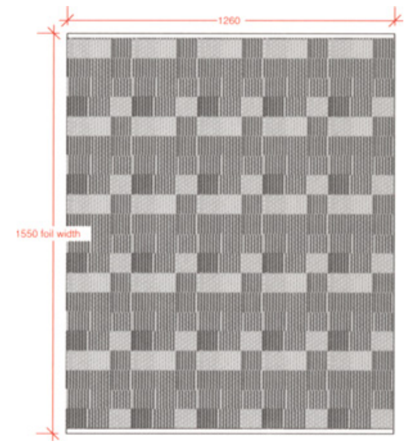

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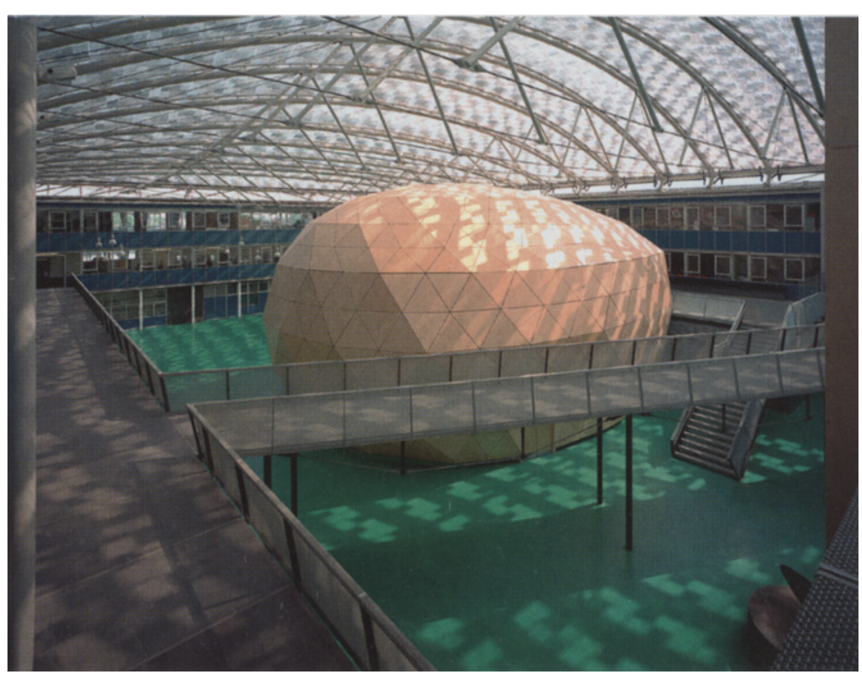
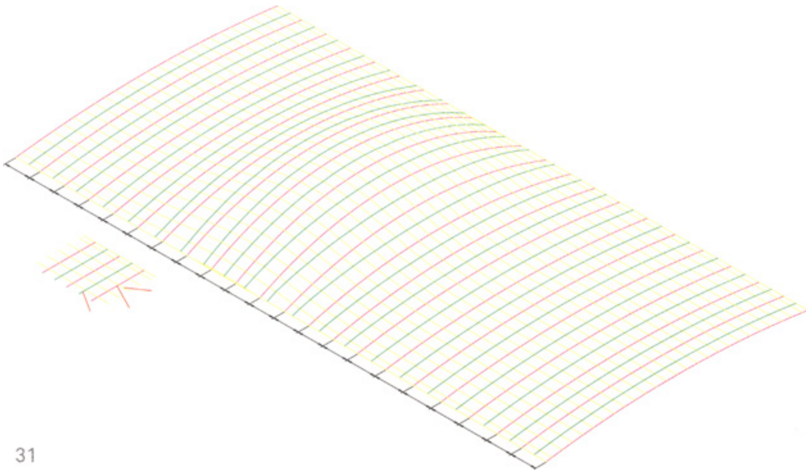


26–27__The two outer foils of the three layer cushions are printed, each with a different pattern. The combination allows 50 percent light transmission when open and 5 percent when the printed foils are superimposed. /
28–29__Outer and middle layer patterns /
30__View of central court /



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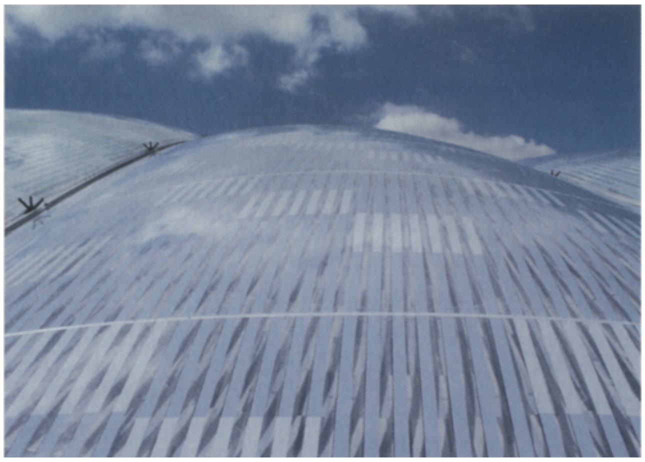

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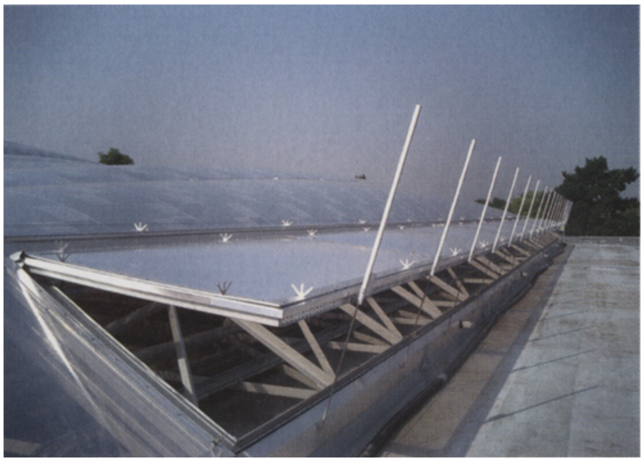

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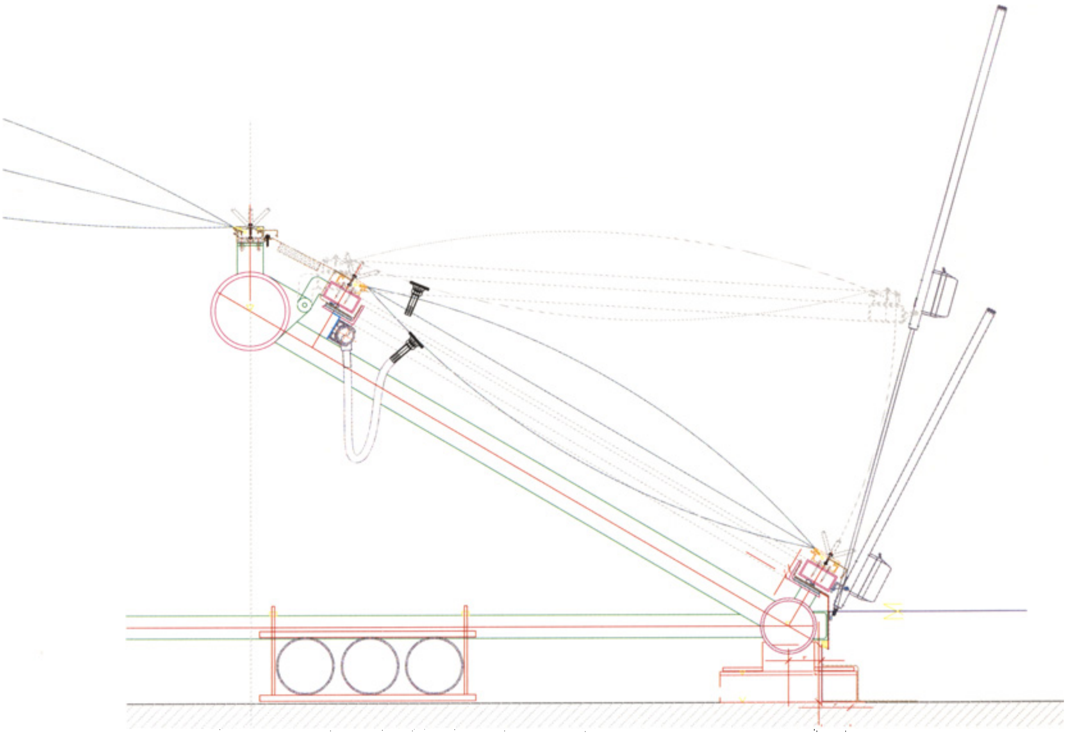

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31__3-D model of roof surface /
32__While internal patterns of light and shadow are pronounced, the external appearance of the variable envelope is subtle and understated. /
33__Opening cushion vents at clerestory level provide natural ventilation, supporting the passive servicing strategy. /
34__Detail section of opening cushion vent /

35

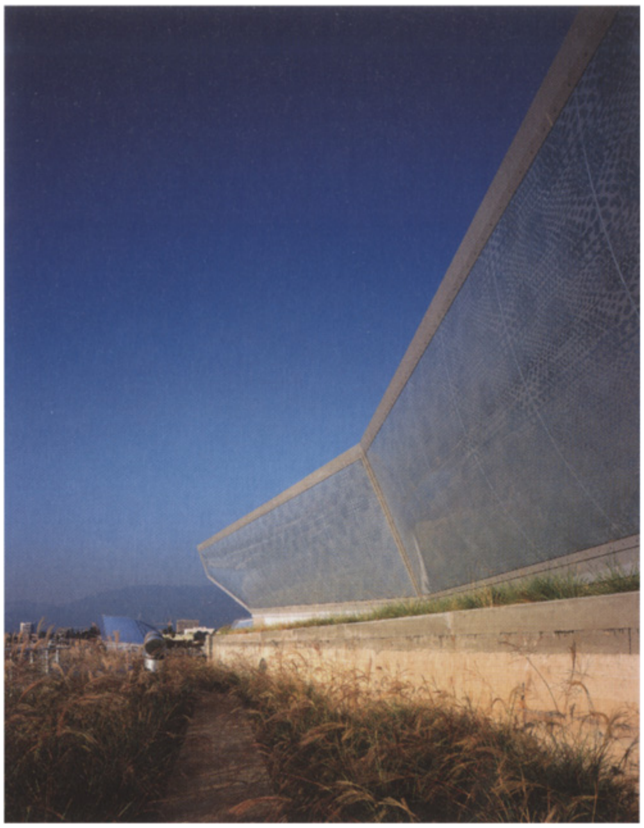
Art Center for the College of Design, Pasadena
Daly Genik Architects, 2004 /
35__ETFE skylights, formed by strategic cuts in an existing concrete envelope, advertise the school's presence in a former industrial zone. /

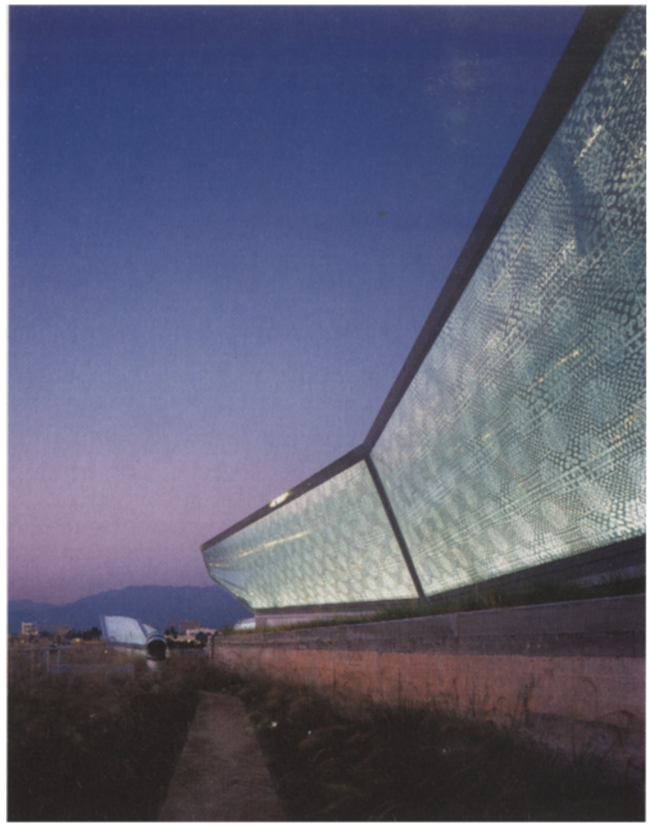
animated quality of light as people move through the space. For evening use and during dark winter months, lighting is provided by pendant fittings hung from the bowstring trusses.

This ETFE roof plays an important role in the goal that the refurbished building consume zero energy. In addition to significantly reducing the amount of external wall and its heat loss, the ETFE cushions allow passive solar gain to combine with heat generated by occupants and electrical lighting to warm the building during cooler months. In summer, the closed patterning reduces solar gain, and natural cross ventilation is provided via a new glazed entry bay at grade and opening ETFE cushions at clerestory level, which are controlled by sensors.

At the outset of the project, demolition of the existing building was considered. However, refurbishment made better sense in terms of sustainability and, because the new ETFE roof transforms latent space, gives the school more generous facilities than could now be built given the stringent government area standards for new schools. In addition to its intended uses, the court is constantly being adapted by the occupants to accommodate social activities and informal learning. With investment in technology as well as facilities, architecture cannot claim to be solely responsible for improved academic performance at Kingsdale, but it seems clear that good school buildings do provide better learning environments, which in turn reduce absenteeism and increase both staff and student self-esteem. The fact that the refurbished building itself is intelligent and a high achiever in energy efficiency and sustainability is an added bonus.

The skylights of the new Art Center for the College of Design in Pasadena are the first application of variable ETFE envelopes in the United States. Completed in 2004, this building is the first phase of the school's expansion from its idyllic hillside campus to a new South Campus in a former industrial zone in the city. A windowless wind tunnel and its technical support building have been transformed into an art school by making surgical cuts in the existing concrete envelope to admit light. Three of these cuts are skylights that flood the primary circulation space and two large studios with daylight. To design the skylights within the project's modest budget, it was critical that they added no more weight to the building than had been





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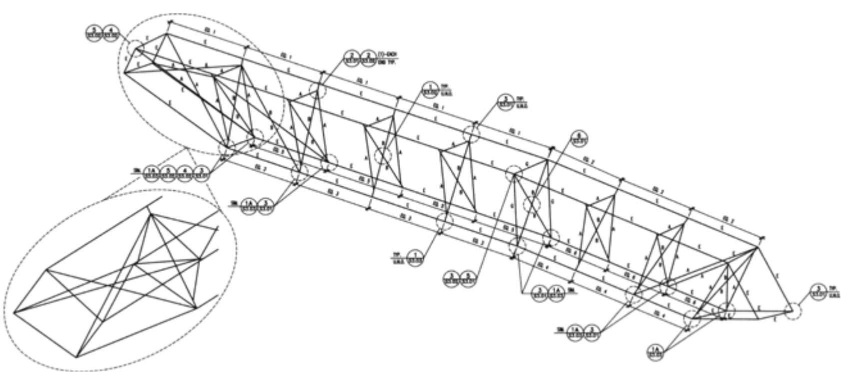

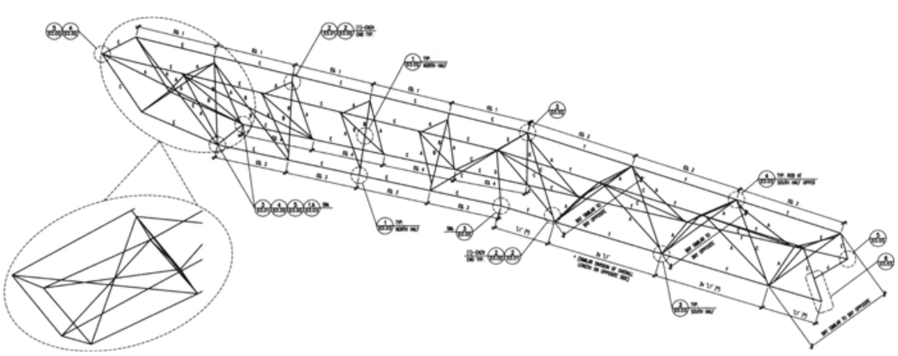

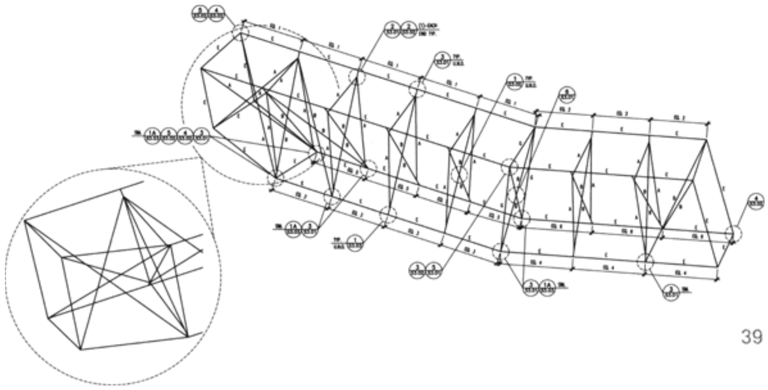

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36–39__The frames of the lightweight skylights are custom angles formed to achieve non-orthogonal geometry and steel rod hangers to support the upturned cantilevered ends. /

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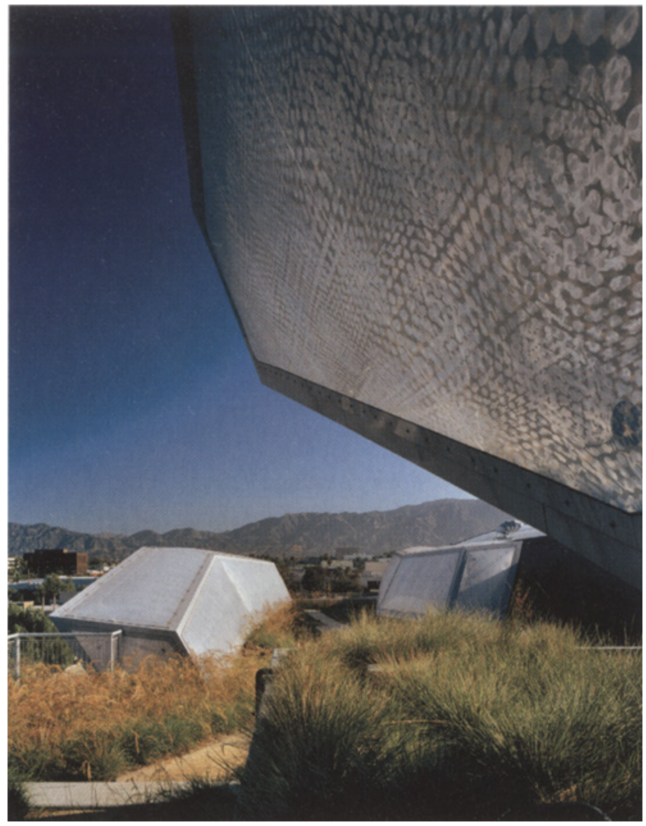

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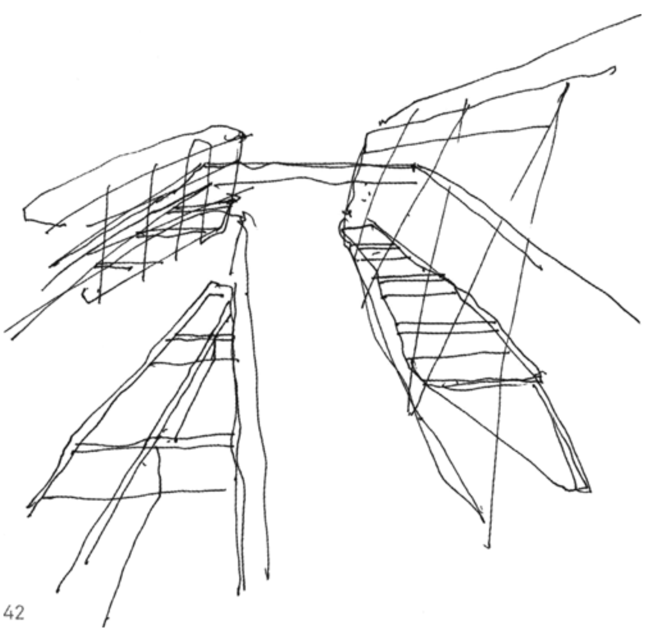

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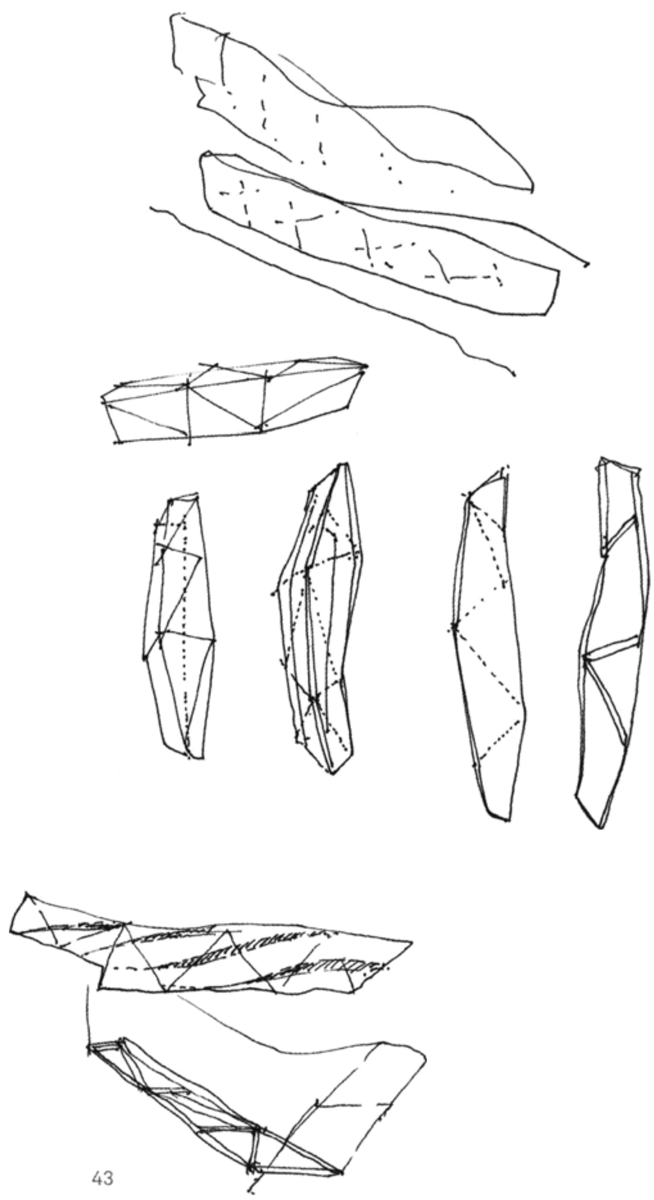

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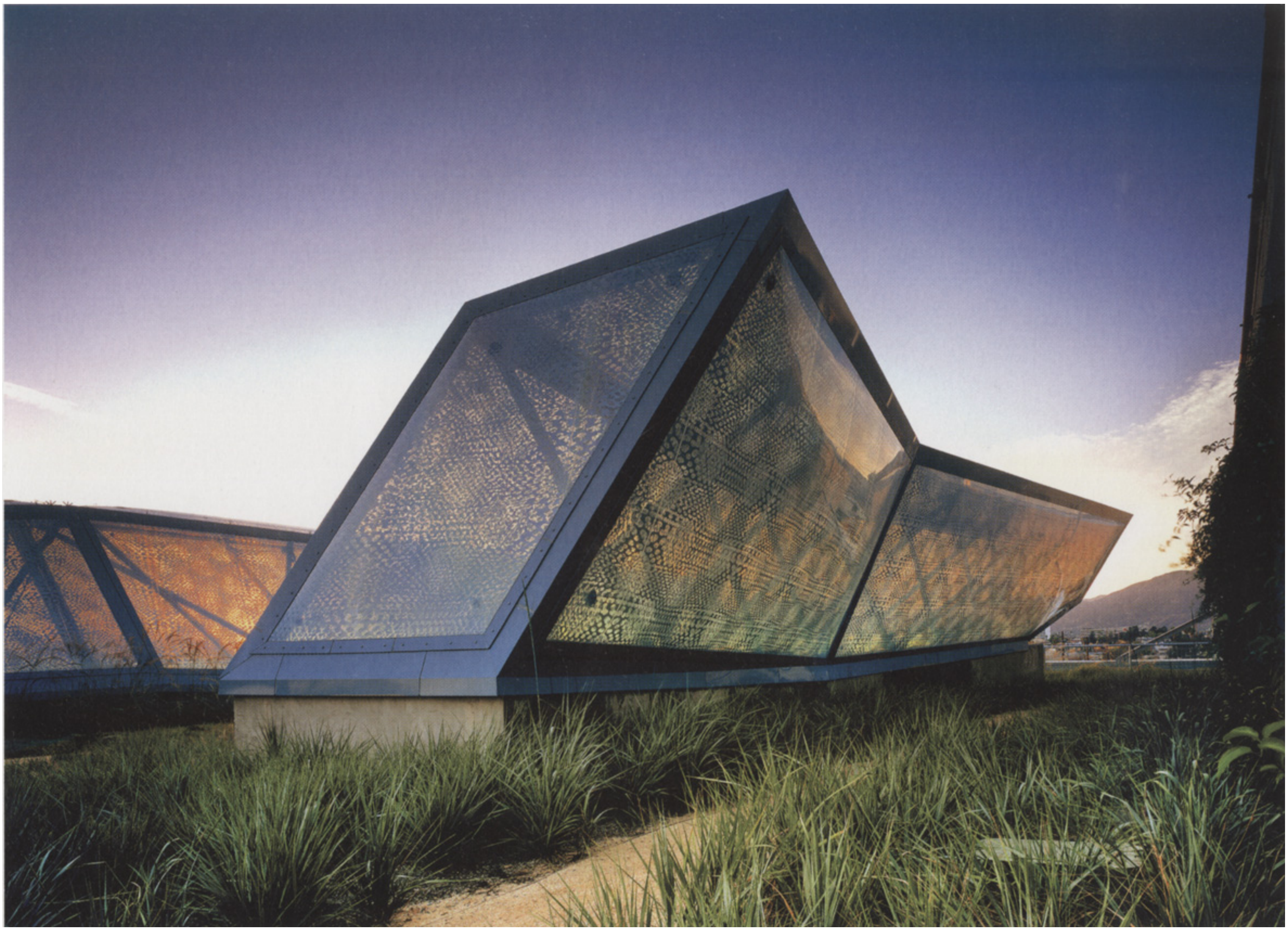

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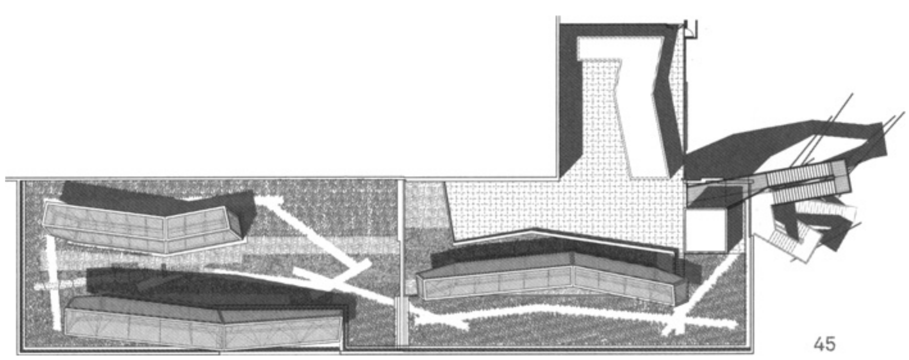

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40–43__The relaxation of orthogonal geometry animates the skylight forms. /
44__The skylights also function as sculptures in the accessible roof landscape. /
45__Roof garden plan /

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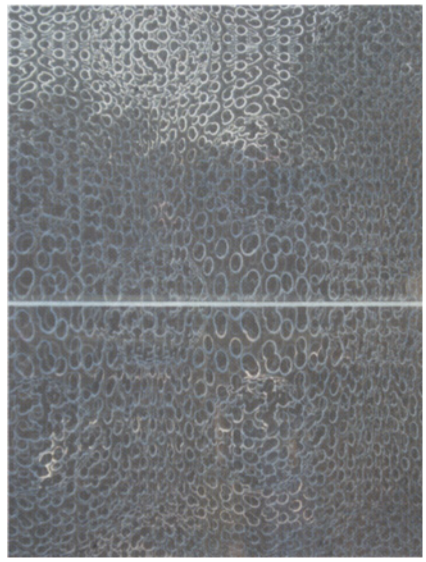

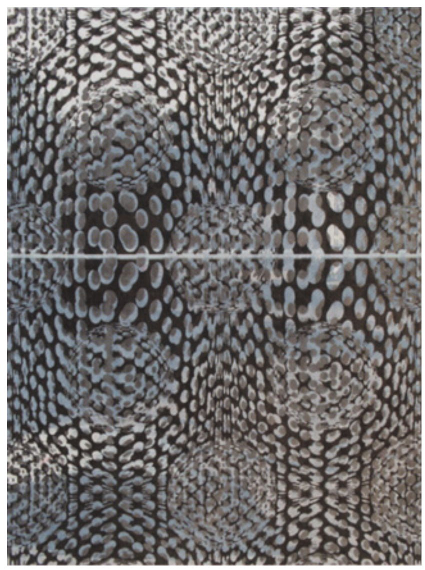

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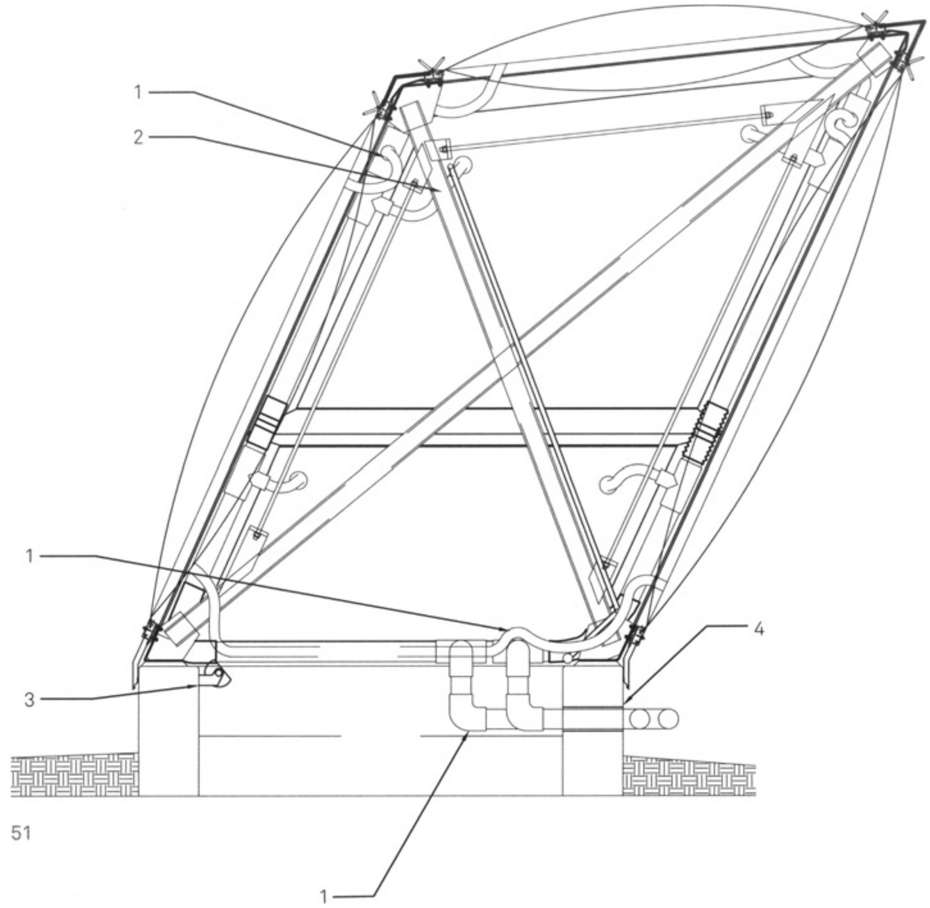
49 50

46__Detail of pattern when the outer and middle layers of foil are superimposed. /
47–50__The printing on the foils overlaps in multiple scales of patterns. Interior view closed (47), interior view open (48), interior view in transition (49), in transition, detail (50) /

removed in making the cuts, so that the existing structure would not have to be upgraded to take additional loads.

The design team researched many enclosure systems including glass, polycarbonate and fabric. Even though all are considered to be lightweight, they generated significant loads because of the stiffness required of their supporting structures. In contrast, ETFE's combination of lightness and flexibility, together with its ability to deflect and capacity for large cushion components, enabled the design team to minimize the weight of the skylights' steel frames. Instead of static orthogonal forms, the skylights – which appear to be tethered to the roof – are animated "not-rectangles" with upturned cantilevered ends.[1] In a quest for lightness, the overall dimensions of the skylights were determined by the largest feasible ETFE components so that each facet, without intermediate joints, is a single cushion. The steel frames are made of custom angles bent from plate to achieve the non-orthogonal geometry, and diagonal steel rod hangers support the cantilevers.

In the three layer cushions, printed graphics control light and manipulate perception, as well as reinforce the aims of the art school by integrating structure with environmental and graphic design. Developed in collaboration with graphic designer Bruce Mau, the pattern is composed of multiple overlapping scales ranging from "golf balls to beach balls," with contrasting patterns printed in silver FEP inks on the outer and middle ETFE films. In an effort to obscure the clear zone required for cushion welds, half circles of the pattern join at each vertical seam. Using variable air pressure to move the middle foil in the cushion, light transmission in the open position is 50 percent and in the closed position, when the two printed foils are superimposed, reduces to 20 percent. Because light bounces as it passes through the printed foils, its transmission is more complex than the simple proportion of clear foil in the pattern and required considerable fine tuning through digital simulations and full-scale mock-ups. The position of the foils is governed by daylight sensors and a timer tuned to the calendar. The steel frames, prefabricated and trucked to site, each in a single piece, were craned into place, with cushion installation quickly completed in situ. The inevitable logic of lightness emerged from the constraints of the existing site cast concrete building and produced skylights that economically modulate both daylight



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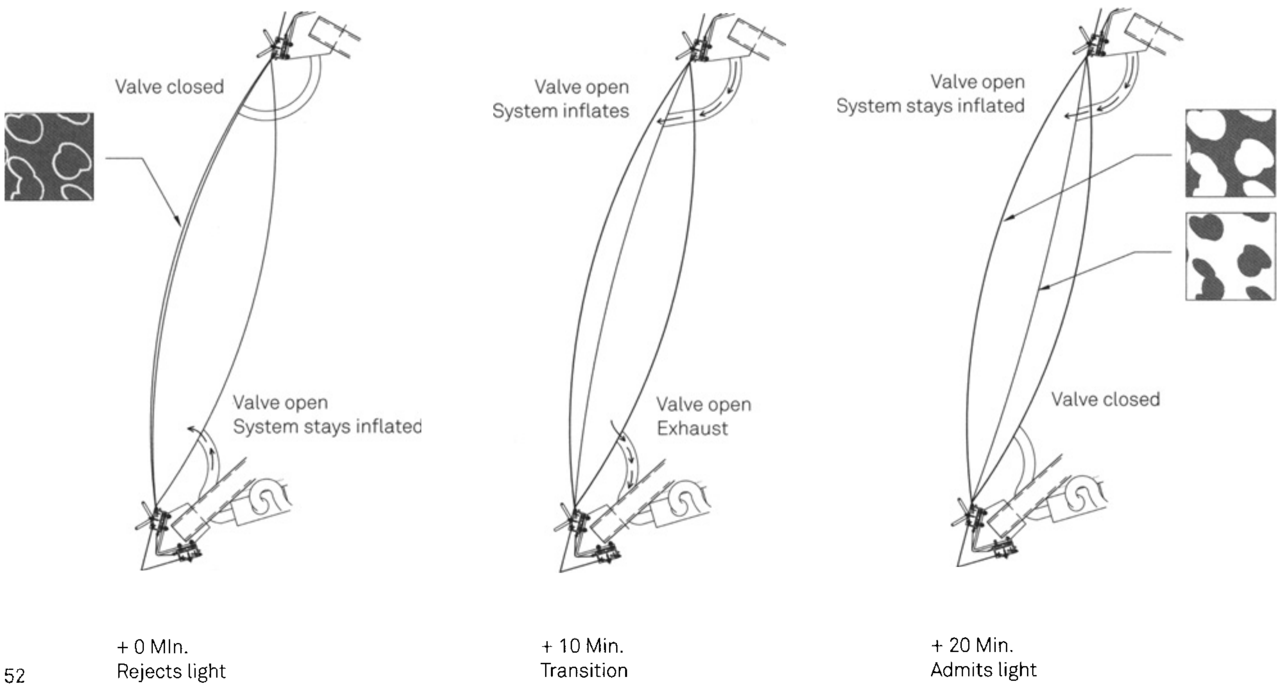

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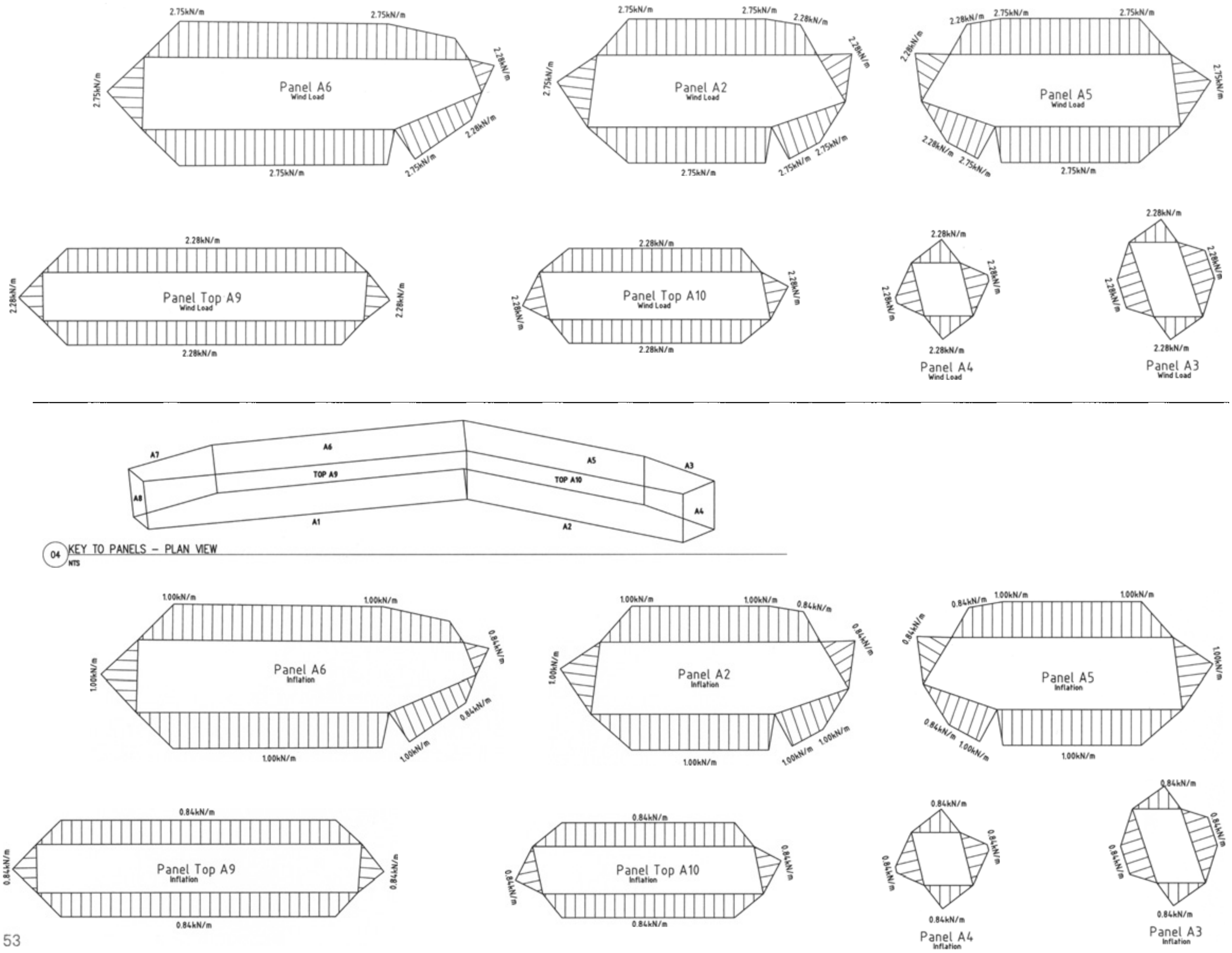
51__Cross section
1 typical pneumatic supply tube
2 skylight support structure
3 lighting fixture
4 concrete curb penetration /
52__Variable positions of middle foil /



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53__ETFE panels /
54–55__The steel frames of the skylights were prefabricated and craned into place, with installation of ETFE cushions carried out on site. /

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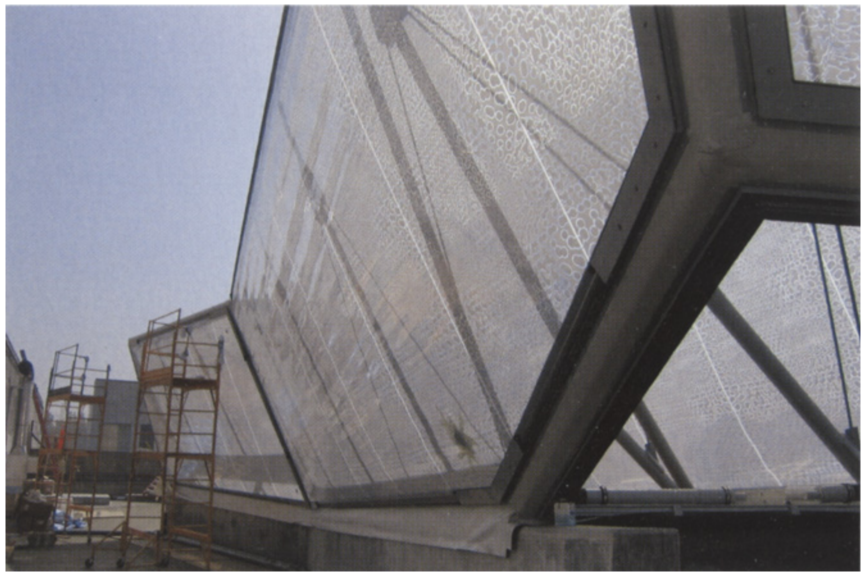

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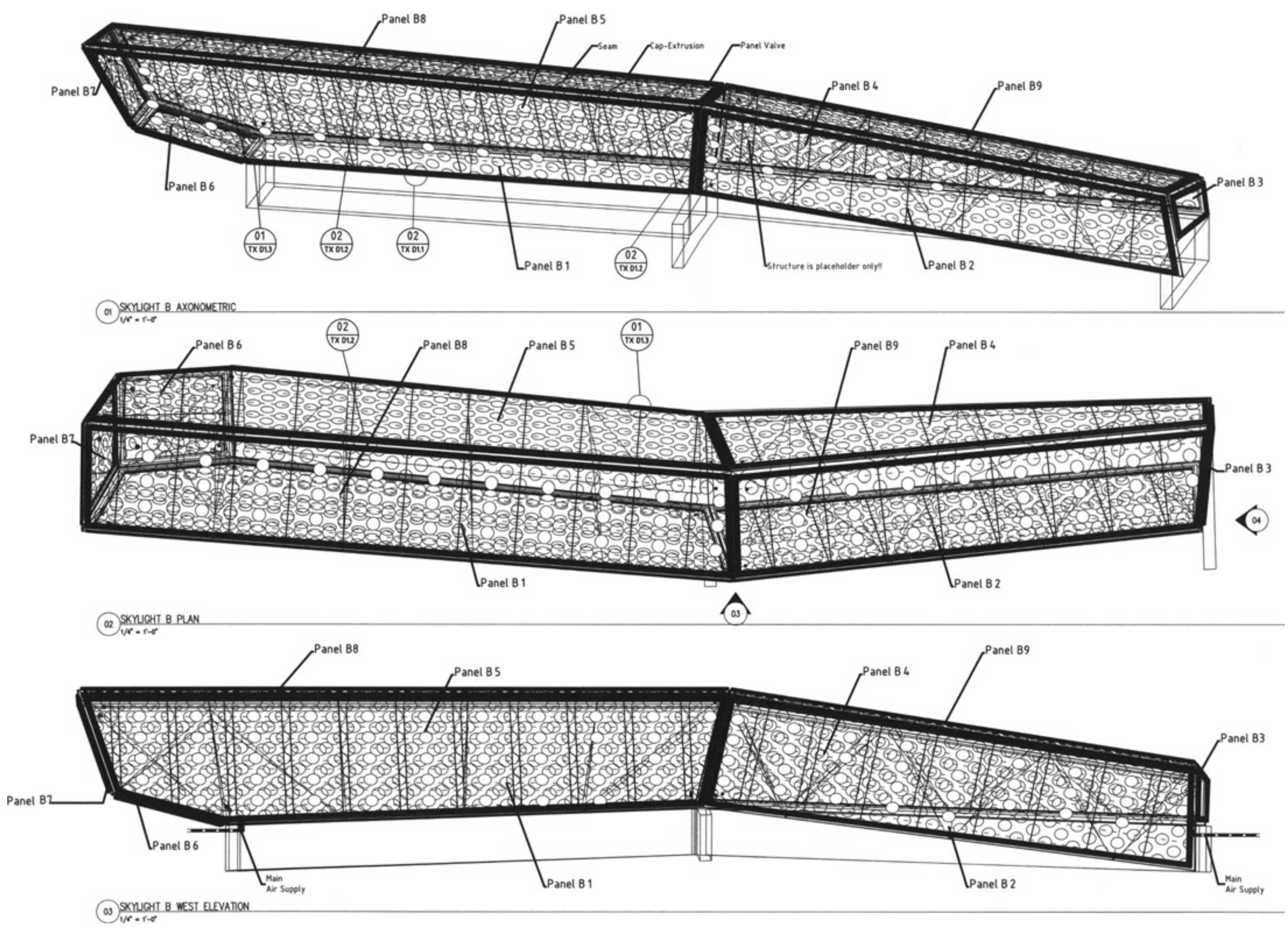

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56–57__Each facet of the skylights comprises a single ETFE cushion. /
58__Skylight axonometric, plan and elevation /

59

John Wheatley College, Glasgow
Ahrends Burton & Koralek, 2007 /
59__Photovoltaics integrated onto the outer face of ETFE cushions augment the energy conservation of this envelope system with energy-producing capability. /

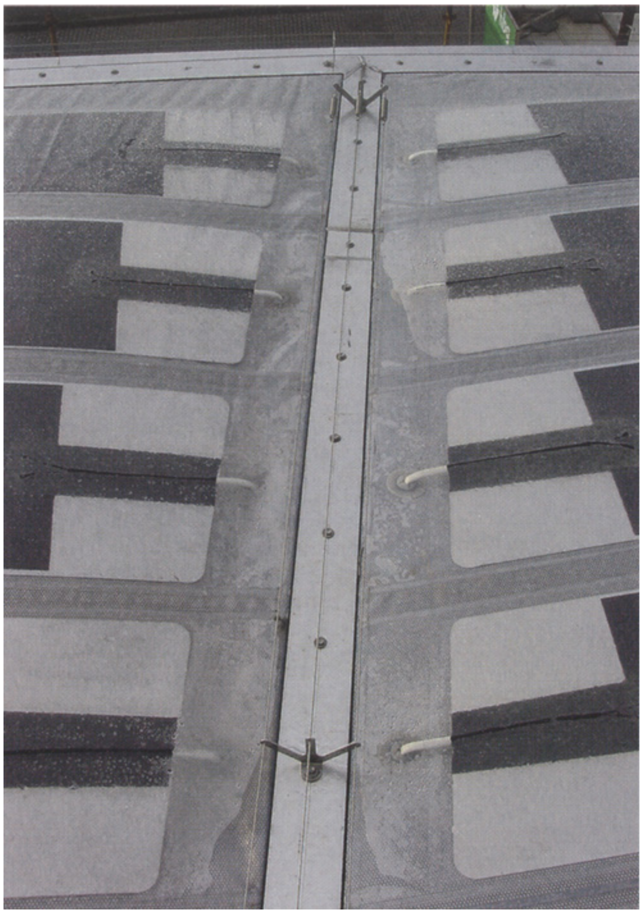
and solar gain. In addition, the supple forms become sculptures that can be enjoyed at close proximity in the accessible landscape of the new planted roof. The sculptural skylights emit light at night, creating a striking sign for the school and a marker of its move to revitalize a former industrial zone in the city.

Servicing accessories

ETFE cushion systems are also proving to be amenable to the incorporation of what might be called accessories, particularly servicing technologies. In addition to conserving energy through the intrinsic insulation value of air and the manipulation of foils by pigments and applied coatings, ETFE cushions can now produce energy. By replacing printed shading patterns with solar cells, solar energy that is unwanted for heating or lighting the building can be harvested. The development of thin-skin flexible photovoltaic cells and triple junction technology allows the absorption of wider ranges of solar energy than conventional mono-crystalline cells and transforms the building skin from an inert surface into an active energy-generating membrane.[2]

The library at John Wheatley College in Glasgow, completed in 2007, is the first ETFE envelope to incorporate photovoltaics. The 3 millimeter thick photovoltaic membrane comprises thin slivers of stainless steel bonded with amorphous silicon to a stainless steel mesh, all encased in a vacuum-formed ETFE wrapper. The flexible fabric, prefabricated in 400 x 3000 millimeter modules, is laminated by being welded into the outer face of the ETFE roof cushions. This 55 square meter installation is modest, more of a political and ethical statement than a producer of power. However, with the technology now developed, photovoltaics in ETFE enclosures will undoubtedly be used for larger applications.

The dynamic control of of air pressure and incorporation of accessory technologies onto cushion surfaces enable ETFE envelopes to react in response to diurnal and seasonal cycles as well as changing weather, and to act by producing energy. Acting and reacting, ETFE cushion systems are increasingly being designed to behave as Reyner Banham envisioned, more like the skin of a living creature than a conventional building envelope.



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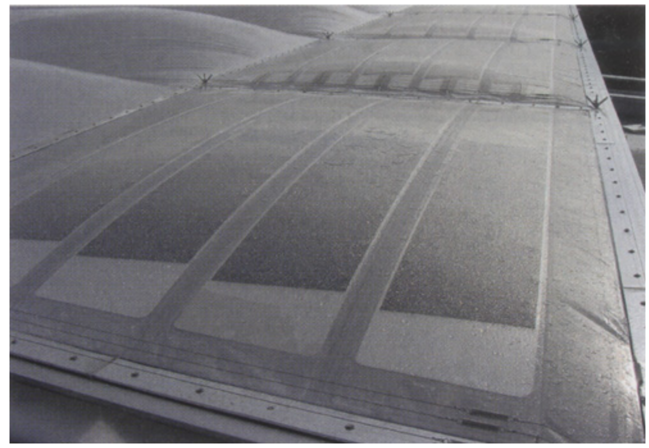

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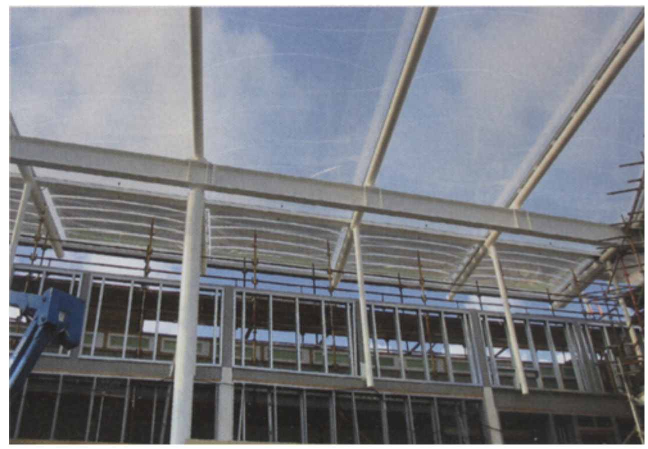

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60–63__The technique of laminating thin-skin flexible photovoltaic cells onto the ETFE membrane holds great potential for more extensive applications. /

1__ The term “not-rectangles” is coined by Michael Sorkin in the essay “Frozen Light” in *architecture + process: gehry talks* (New York: Universe Publishing) 2002, in which he discusses the distortion of Platonic solids as a technique of cartoon animation that, because of digital design and fabrication, is now possible in architecture.

2__ Texlon PV (photovoltaics) is a patented product of Vector Foiltec.

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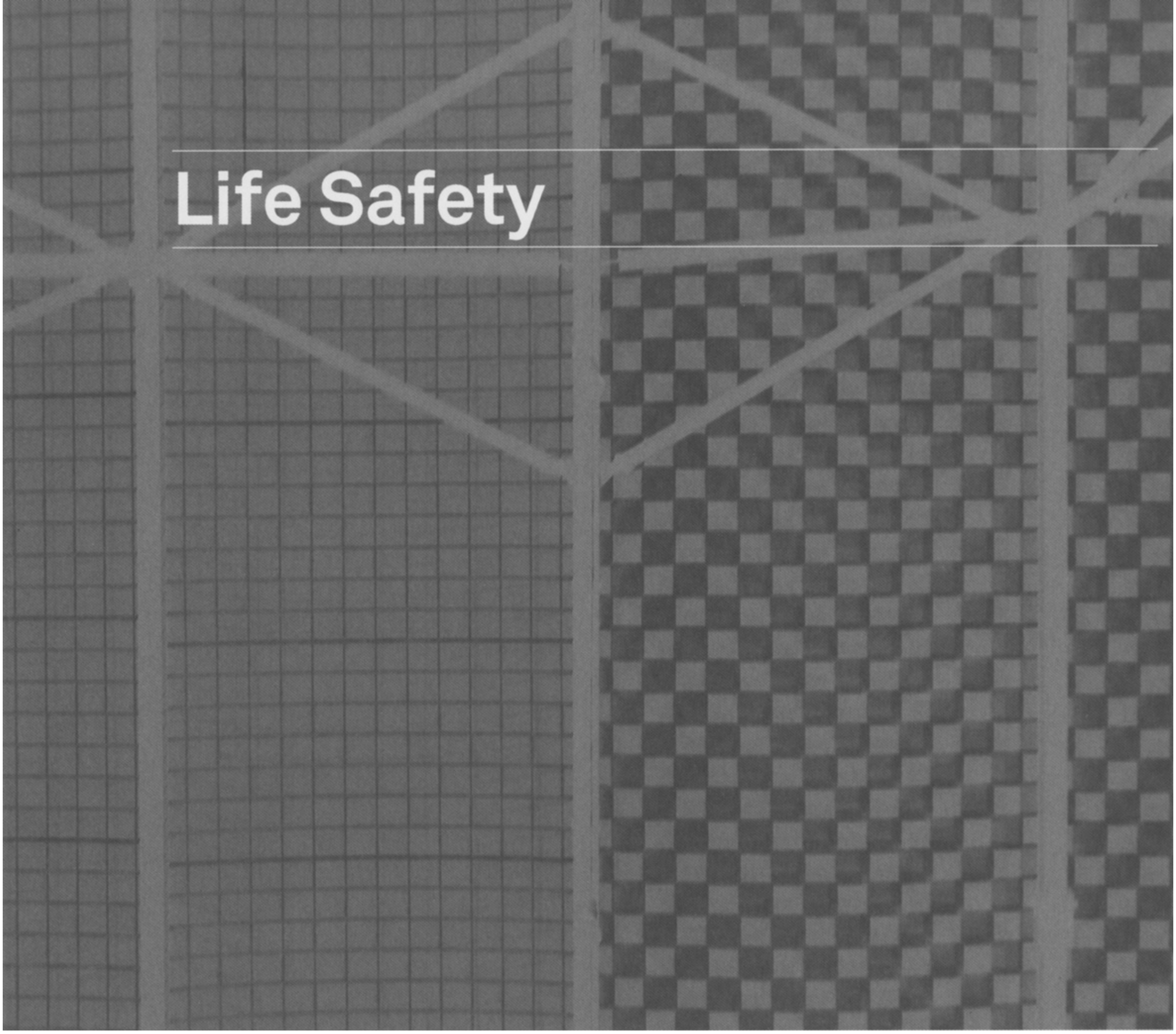

Life Safety

While architects and engineers seek to design buildings to resist extreme events such as fires, explosions, severe weather and earthquakes, they must also consider the implications for life safety should such events occur. When ETFE was first suggested for architectural use, building officials were naturally cautious, allowing it to be used only with constraints. Their caution was based upon experiences of other plastic materials, which were known to burn, give off toxic fumes or drip in a molten state in fires, posing significant risks to life safety. Since being approved, initially by the German building authorities in 1984, then in the UK in 1985, ETFE has gained wide acceptance in many regulatory domains. The tables have turned, and projects are now being approved on the condition that ETFE is not merely tolerated, but required for the building envelope. A key factor that has brought about this change is the life safety performance of ETFE cushion systems, which combines their soft structural and environmental characteristics.

Fire

One of the most significant attributes of ETFE compared to other plastic building materials is its fire performance which, together with its light weight, has led to applications in fields such as the aerospace industry, where NASA and manufacturers like Airbus use it as an electrical insulant. Although combustible, ETFE is inherently low in flammability because of the presence of fluorine in its chemical structure and a low oxygen index, which renders the material self-extinguishing. In contrast with materials like PVC, which readily gives off dioxins when burned, ETFE produces toxic fumes only when burned at temperatures above 800 degrees Celsius. However, given the quantities of ETFE typically present, this is insignificant in comparison with the highly toxic carbon monoxide generated by the fire itself. Above 200 degrees Celsius, the foil softens and, as it is under tension, fails. In the cushion systems used for building enclosures, because the ETFE foil is prestressed by inflation, it shrinks away from the plume of hot gases and vents fire to the atmosphere. Any remnants of the lightweight foil are swept up and away by escaping gases so that the material does not fall onto the building's occupants. The self-venting of ETFE also prevents heat build up that can cause an explosion, flashover or collapse of a building's primary structure. Because self-venting

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1__Because they are flexible and lightweight, opening ETFE cushion vents can be much larger than conventional smoke vents. /
2__For the hot wire smoke vent, a wire around the cushion perimeter is activated to cut the foils, thus venting the fire to the atmosphere. /

instantly transforms an interior into an open-air space, this behavior allows atria to be classified as external spaces, which results in many cost savings to the base building envelope. This principle was applied to the enclosed light-wells of the refurbished Her Majesty's Treasury in London, where the historic courtyard façades were not required to be fire rated, an essential factor in enabling the natural ventilation scheme – a key component of the sustainable servicing strategy – to work.

ETFE has been successfully submitted to fire testing by authorities around the world including the European Union, the United States, Russia and China. Like many specialized buildings, the enclosed volume of the National Aquatics Center in Beijing is larger than the maximum compartment size permitted by the Chinese building codes. Its fire engineering therefore had to be developed from first principles and presented considerable challenges. Far from being predisposed to support the use of ETFE, Chinese officials initially prohibited ETFE despite the fact that it is non-combustible. However, this objection was overcome by demonstrating the way in which the material's self-venting properties mitigate risk to life safety.

To deal with cold smoke and fire conditions in which temperatures do not reach 200 degrees Celsius, ETFE cushions can incorporate conventional opening vents, opening cushion vents and proprietary smoke vents. Opening ETFE cushion vents are more efficient than conventional vents because of their size. The largest ETFE cushion vent built to date comprises a single cushion that is 25 meters long and 3 meters high, a size that is feasible because deflection is not critical for ETFE cushion assemblies. In the proprietary realm, recently developed hot wire smoke vents feature a 4 millimeter diameter thermal resistance wire – a robust technology developed for keeping oil pipes in the Arctic at a constant temperature – which is incorporated in the edge detail of the cushion and activated by fire sensors connected to the building management system.[1] On activation, the wire heats up and, operating as a hot knife, cuts the foils to vent the fire to the atmosphere. Within 60 seconds of activation, 50 percent of a cushion's area is vented, and 100 percent within 90 seconds. At this point, the foil is cut on all except one edge of the cushion, where it remains attached and hanging. This 100 percent efficient, dynamic free area compares



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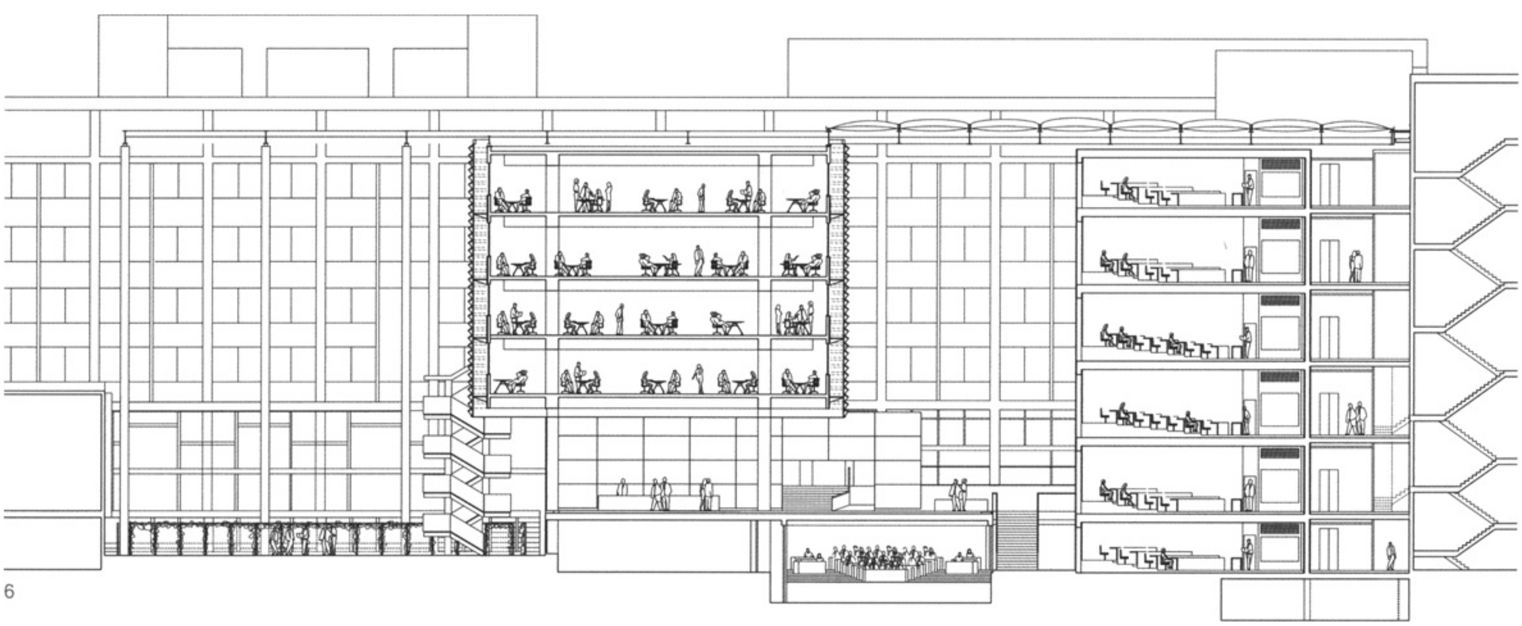

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Tanaka Business School, Imperial College, London
Foster and Partners, 2004 /
3–7__An environmental envelope with an ETFE cushion roof knits existing and new buildings together to create a social center for the school. /

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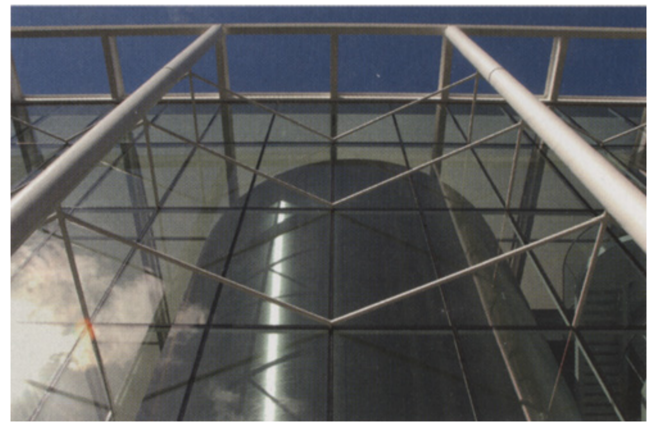

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8–10__The ETFE roof, seen through the glazed façade, incorporates hot wire smoke vents, enabling the atrium to be classified as an external space. /

favorably to approximately 50 percent for louvers and 60 percent for conventional opening vents, where the geometric free area is significantly reduced by turbulent edge effects. In addition, hot wire smoke vents are around 10 percent of the cost of opening vents, although they must be replaced after activation. For ETFE envelopes, a hybrid smoke clearance strategy is therefore recommended, which begins with opening vents followed by hot wire cushions activated in sequence until smoke is cleared, thus avoiding the need for mechanical smoke extraction.

The Tanaka Business School at Imperial College in London is a project that derives many benefits from ETFE's fire performance. Completed in 2004, it also demonstrates the potential of ETFE envelopes to knit together new and existing buildings. The school is spliced into a tight urban site surrounded by 1960s academic buildings and the listed historic Royal School of Mines. Teaching spaces are concentrated in a new six story drum clad with stainless steel fins, while faculty and administration offices are housed in refurbished floors of the School of Mines. An environmental envelope with a glazed street façade and an ETFE cushion roof unites these discrete components into a cohesive scheme, creating an atrium that is both the social focus of the school and a generous colonnaded entrance to Imperial College from Exhibition Road. In addition to its urban and social attributes, this atrium is the first application of hot wire smoke vent technology. Because of the ETFE envelope and its smoke vents, the atrium is classified as an external space. All existing windows to the retained façade were therefore allowed to continue to naturally ventilate into the new atrium foyer, thus avoiding the need for expensive fire protection and new mechanical and electrical systems.

Failure

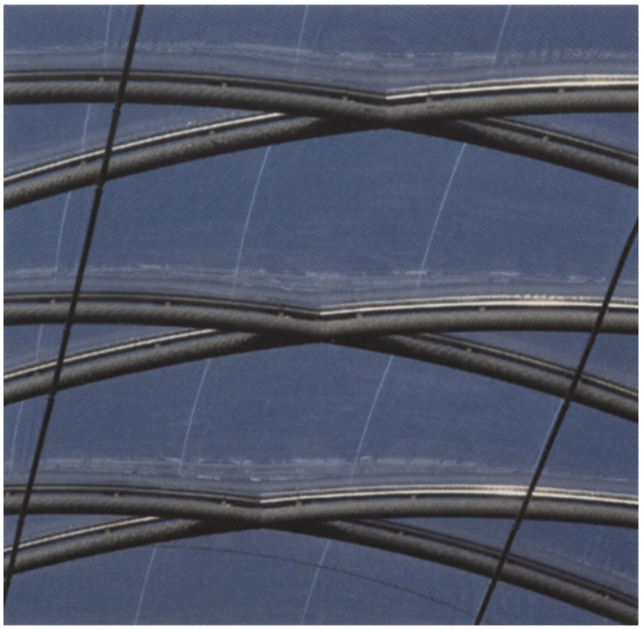
Unlike glass, ETFE cushions do not break and fall out of their frames, a further asset in terms of life safety. The DomAquarée in Berlin, completed in 2004, demonstrates how this attribute has been deployed to resolve an unusual safety issue. Located at the intersection of Spreegasse and Heilig-Geist-Gasse, the mixed-use project includes shops, entertainment, housing, offices and a hotel. The buildings, as prescribed by the urban plan, are "solid houses" with traditionally proportioned stone façades. However,

DomAquarée, Berlin
nps tchoban voss architekten, 2004 /
11__The ETFE atrium roof eliminates the risk to the structural integrity of a five story aquarium that would have been posed by the possible failure of a glazed roof. /

the streets and their crossing are enclosed with lightweight ETFE cushion roofs. A central atrium features a five story high aquarium that is the focus of the hotel lobby. In addition, there is an office atrium and a shopping arcade. All three spaces were originally designed with steel and glass roofs. However, because the aquarium is an audacious piece of engineering in itself, there was concern about the risk posed to its structural integrity by the possibility of glass falling from the roof. ETFE's transparency, light weight, ease of accommodating irregular geometries and "friendly" mode of failure resolved this concern.

Each roof in the development has a different specification. The office and shopping atria feature fixed ETFE membranes – three layer clear cushions for the offices, which are designed principally to enhance insulation values, and two layer clear cushions that simply serve as an umbrella for weather protection in the shopping arcade. The highest level of performance is achieved by the four layer printed cushions of the hotel atrium, which comprise a variable skin that provides changing levels of thermal insulation and solar shading for both the aquarium and hotel rooms facing the atrium. The pattern is an irregular fine dot screen, which is designed to appear as invisible as possible. In summer, when the printed foils are closed and superimposed, light transmission is 35 percent; in winter, the foils are held apart to enhance U-values and increase light transmission to approximately 50 percent. In addition, the structure and cushions are designed so that the central ring of this roof can be removed to allow access for aquarium maintenance. These ETFE envelopes and their supporting structures were half the cost of the original steel and glass proposal, with both construction and life cycle savings resulting from lighter and less rigid structure and from the omission of the costly gantries and connection hooks needed for cleaning glass.

The benign failure mode of ETFE opens up the potential of even broader applications. Widely published glass failures caused by nickel sulphide inclusions, which continue to raise concerns about overhead glazing installations despite heat soaking and other treatments, have motivated many developers to consider safer options. In the UK, because of the potential life safety and economic consequences of this problem, a number of shopping centers with glazed atria will only use overhead glazing if



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12–15__A range of ETFE cushion types provides varying levels of performance for open air shopping streets, office atria and a hotel atrium, where the aquarium is located. /

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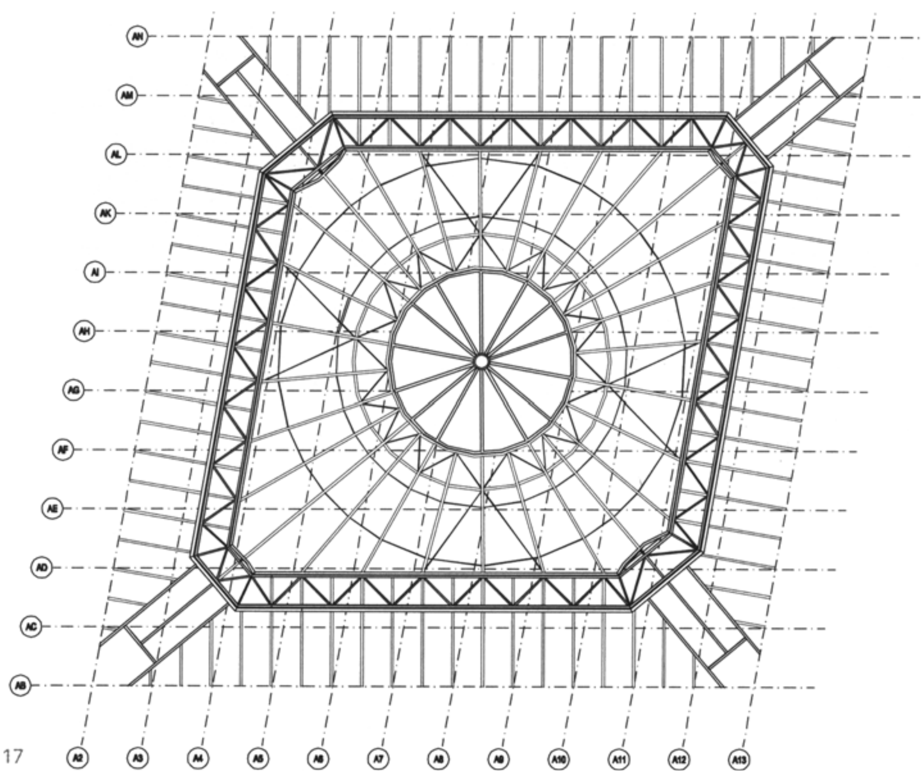

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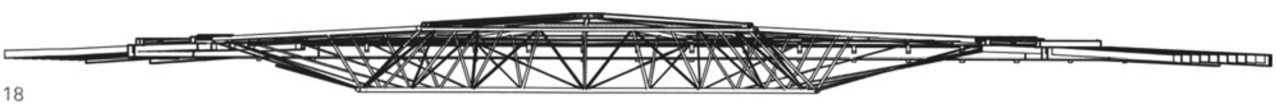

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16__Aerial view showing several types of ETFE roofs /
17–19__Plan, section and isometric of the hotel atrium structure /

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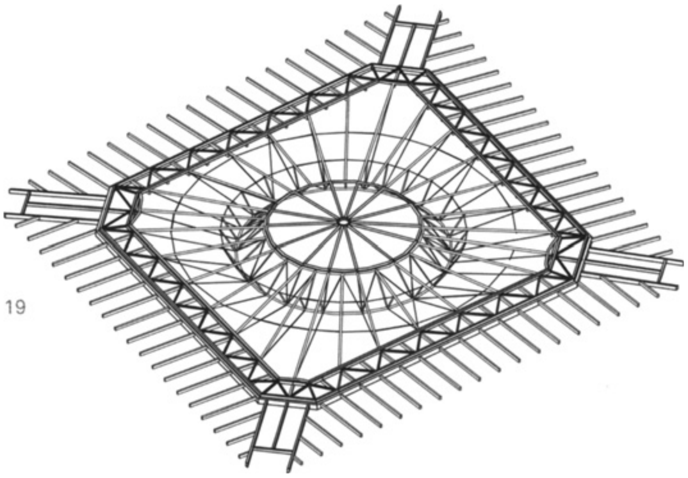

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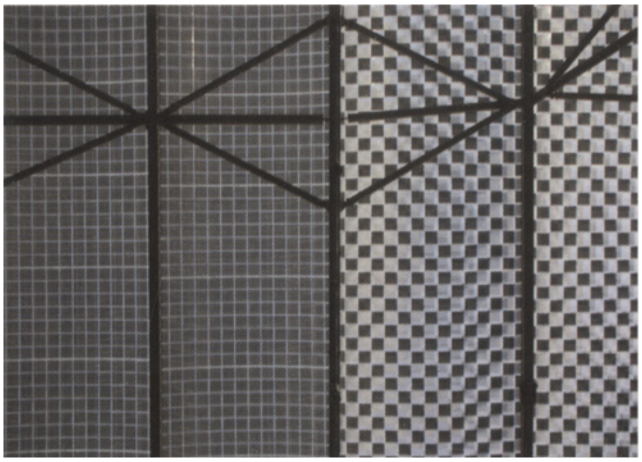
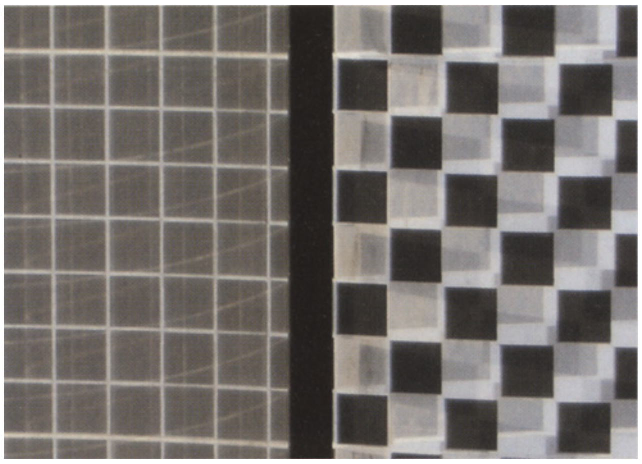
20–23__The central ring of the hotel's atrium roof can be removed for aquarium maintenance. A four layer printed variable ETFE cushion envelope enables thermal insulation and solar shading to be carefully controlled. /





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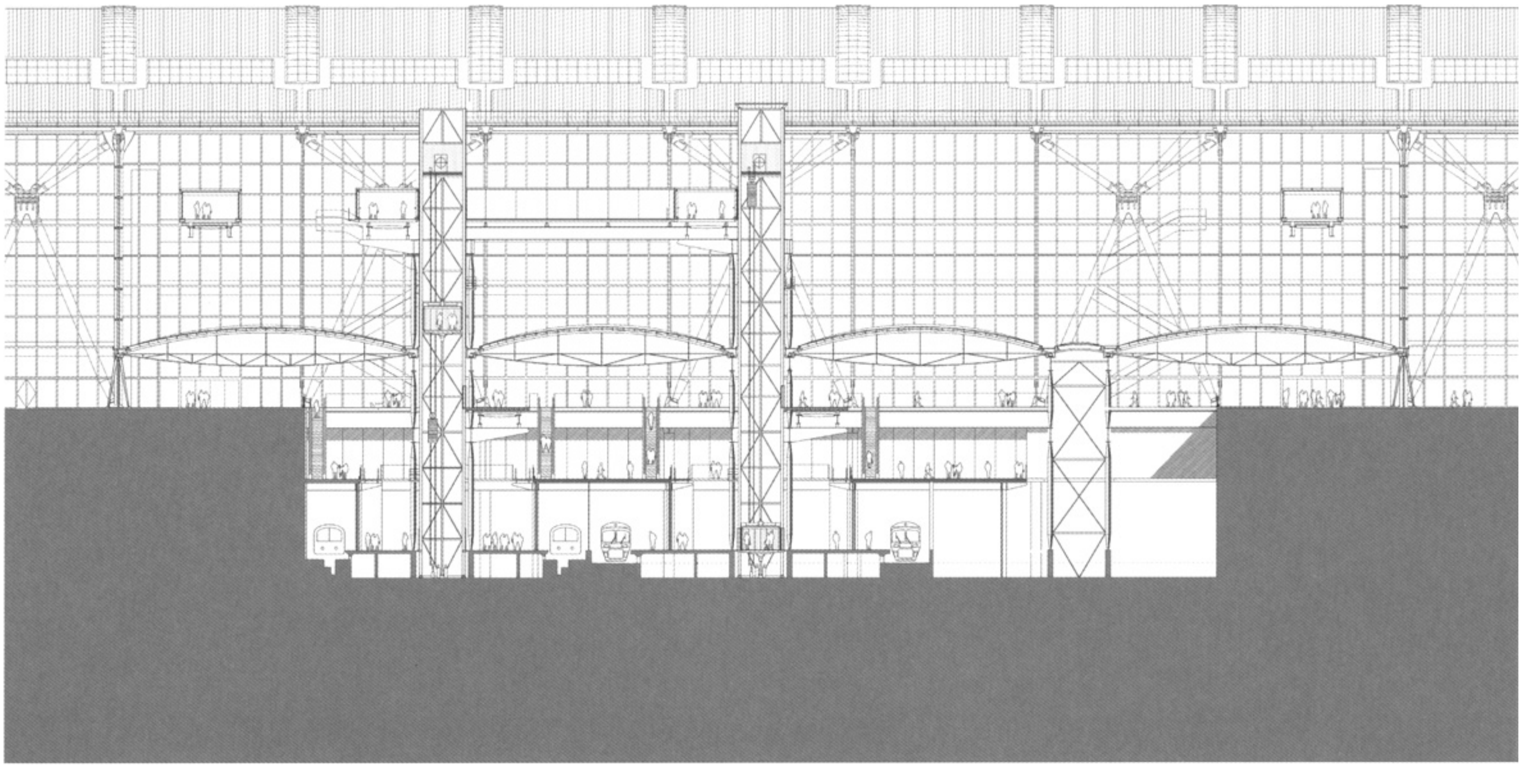
The Mall, Athens
Ergotex, 2005 /
24–25__The variable cushion roof is seen in the closed or superimposed position on the left and open on the right. /
26–27__A variable ETFE cushion roof, installed to minimize solar gain in a former open-air shopping center, also addresses safety concerns arising from the potential failure of overhead glazing installations. /



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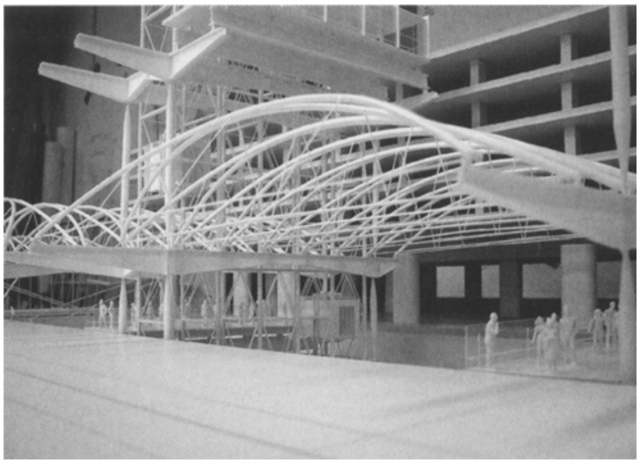
Transport Interchange, Terminal 5, Heathrow Airport, London
Richard Rogers Partnership, 2008 /
28__The ETFE cushion roof of the Transport Interchange links the new terminal to a parking structure and bus station, and to train platforms below grade. /

the design incorporates stainless steel mesh netting to reduce risk of injury in the event of falling glass. ETFE was used to address this issue at The Mall in Athens, an open-air shopping precinct constructed for the 2006 Olympics, which has subsequently been enclosed with an ETFE cushion roof, a variable skin that minimizes solar gain, and which has inspired many other retail developments in the locality.

Earthquakes, storms and explosions

ETFE's ability to take extremely high short-term loading, combined with its fluid damping mechanism and high tolerance for deflection, make it well suited for earthquake and severe weather applications, or where there is a risk of explosion. In testing to simulate hurricane conditions, for example, three layer ETFE cushions have performed well. Although the outer two layers of foil have been breached, the innermost layer has consistently remained intact. Explosion tests have also been carried out to subject cushions to bomb blast conditions, and these tests have demonstrated that the foil absorbs very high instantaneous loadings without risk of injury to personnel.

This attribute has opened up new applications for ETFE, notably for government and institutional buildings and transportation infrastructure, which are increasingly the target of attacks. It was an important consideration in the design of HM Treasury in London and the British Embassy in Istanbul, where the former glass roof of the atrium, destroyed by a bomb in 2004, has now been replaced by ETFE cushions. Likewise, the new Terminal 5 at London's Heathrow Airport, which opened in 2008, is a project that was in the making for more than ten years, a period when security risks increased significantly. In response to Lockerbie, the World Trade Center attacks and the bombing of Barajas Airport in Madrid, BAA required blast-resistant material assemblies for Terminal 5 that produce no sharp shards in the event of an explosion. This has been achieved with a complex glazing specification for the terminal itself and with an ETFE cushion roof canopy for the Transport Interchange. The interchange links the new terminal with a bus station, a multi-story car park, the Underground and local, regional and international train services. In contrast with the typical terminal forecourt that is consequently dominated by vehicular



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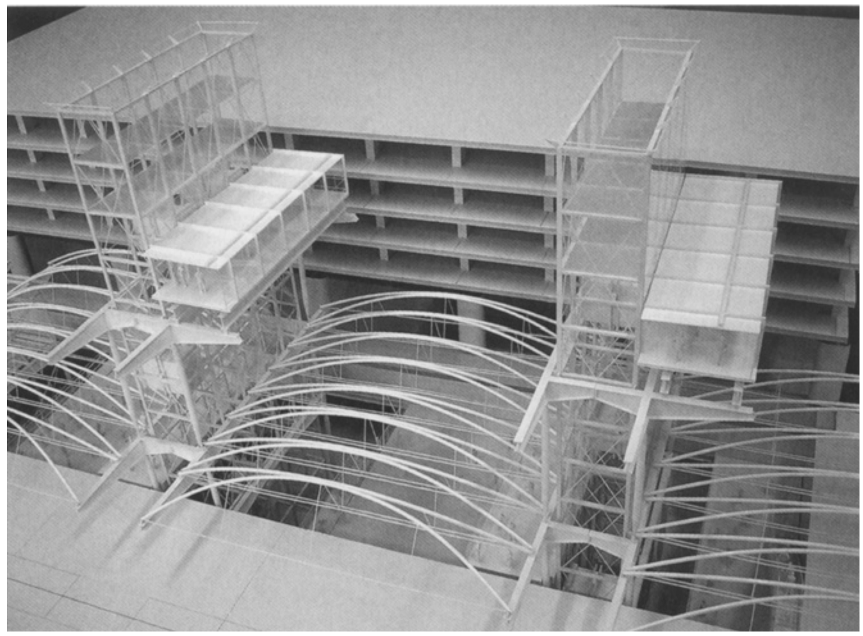

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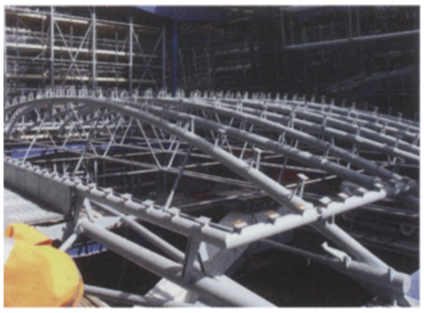
29–30__Shaped wide flange steel girders span between the car park structure and the new terminal, carrying transverse bowstring trusses. /

transportation, the forecourt of Terminal 5 is a generous pedestrian plaza with mature trees. The Transport Interchange, situated at the north end of this plaza, is organized around three banks of lifts that shuttle arriving and departing passengers to and from trains, cars and buses.

The ETFE roof of the Transport Interchange is supported by wide flange steel girders, shaped to reflect the bending moment diagram, which are supported off the outer core of the lift towers. Double-curved tubular bowstring trusses span between girders, forming a series of parallel vaults. Instead of placing the cushion edge extrusions directly on the vault structure, the joint is articulated by elegant triangulated brackets, which hold the ETFE cushions approximately 200 millimeters above the trusses so that they appear to float. The two layer cushions – cigar-shaped with an infill module between – are printed with a matrix of 30–50 millimeter diameter silver dots. These large dots avoid the illusion of a dirty surface that can arise from too fine a pattern, and they give definition to the clear membrane, producing a dappled effect like the tree canopy. The interchange thus becomes an extension of the open-air plaza and, through generous voids, enables daylight to penetrate to the train platforms several stories below. This roof both meets BAA's stringent life safety requirements and transforms the experience of passengers.

Notwithstanding its soft structural attributes and benign mode of failure, ETFE is extremely robust. During the construction of Southern Cross Station in Melbourne, union labor threatened to stop work due to concerns about workmen falling through the ETFE skylights. This issue was resolved by dropping sandbags of the same weight as the union officials from a height of more than 5 meters onto the inflated cushions. The ETFE did not rupture, earning the roof an important non-fragile rating. The unions, to their credit, then wholeheartedly supported the technology, enabling work to proceed with confidence. The broader implication of this result is that external access for installation and maintenance of ETFE cushion enclosures does not require costly safety installations and is therefore easy and economic to provide.

1__ Texlon SV is a patented product of Vector Foiltec.



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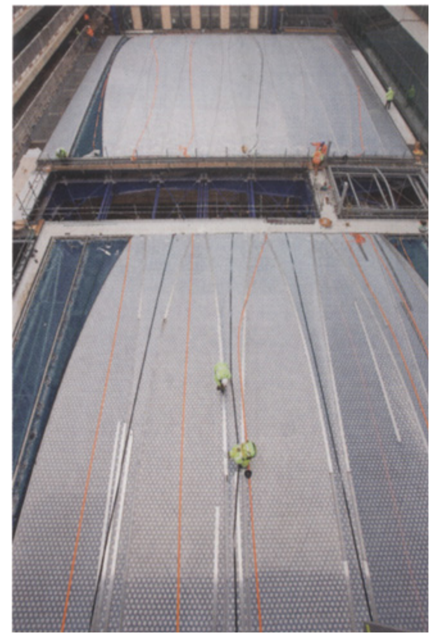

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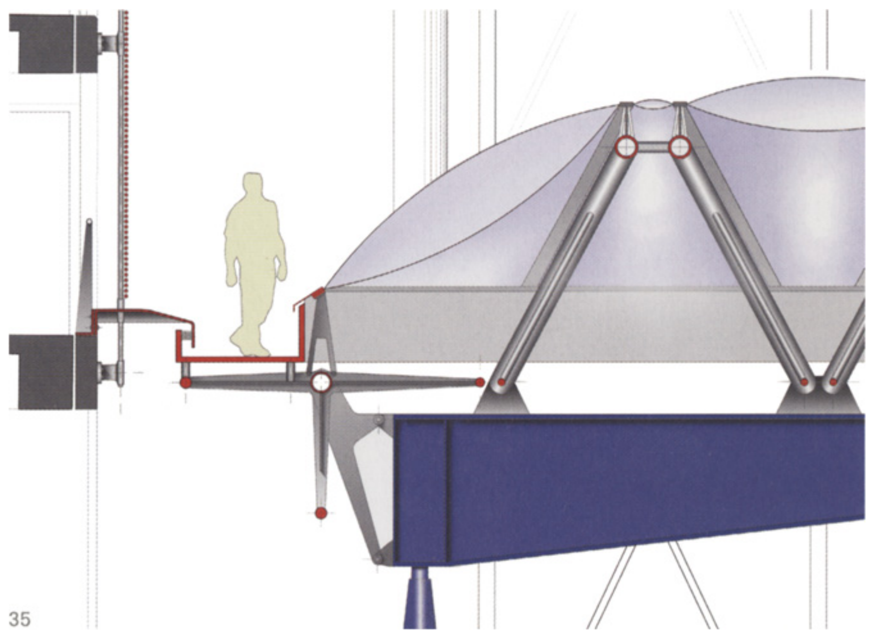

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31–35__Double-curved bowstring trusses are clad with two layer printed ETFE cushions, which meet BAA's stringent life safety requirements and create a concourse dappled with light. /

The Communicative Skin

Reflecting upon the continuing evolution of the hollow wall, Sheila Kennedy notes that, as services are becoming miniaturized, they are migrating from the interstices to the surface itself and are becoming interactive, combining material and media.[1] ETFE cushion systems have begun to demonstrate the potential of this migration. In addition to producing power through the incorporation of photovoltaic cells onto the surface of cushions, the reflectivity of ETFE can be manipulated to enable the film to capture projected light. This can be done during the extrusion process, using an embossed roller to make a micro-pattern of ridges that scatters light passing through the foil, or by printing on the foil's surface. This phenomenon has been exploited in projects like the Air Pavilion at Magna, where the cushion envelope is animated by images of clouds that are projected on the inner face of the translucent matte ETFE enclosure and diffused by the cushions, causing the external envelope to radiate with color. Similarly, in the Heron Quays Station of London's Docklands Light Railway, completed in 2003, fluorescent tubes behind translucent blue ETFE foil cushions create an animated installation that doubles as work of art and sign.

Light show

This potential for ETFE envelopes to become charismatic and communicative was a key consideration in the design of the Allianz Arena near Munich. When the competitionwinning scheme for the new soccer stadium was announced in 2002, it was dubbed the "rubber dinghy" by the press, a nickname strikingly reminiscent of Reyner Banham's common inflated sea horse. Opened in 2005, the stadium does indeed mix high art and popular culture. Giving few clues to reveal its scale, the arena is an enormous mute minimalist vessel sited in an open landscape next to the autobahn, but when a match is being played, it transforms into an animated Las Vegas-scaled sign.

Although it appears to be deceptively simple, the form of the stadium is complex. Three tiers of steeply raked precast concrete seating ensure that all 66,000 spectators are close to the action and have good sightlines. The seating is supported by a concrete frame that combines in situ and precast components. Concrete slabs, together with precast concrete stairs that spiral around the perimeter, brace the double-curved form. In addition to carrying the seating, the concrete superstructure supports 60 meter

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Heron Quays Station, London
Alsop Architects, 2003 /
1–3__Programmed colored lights behind blue ETFE cushions create abstract friezes above train platforms. /

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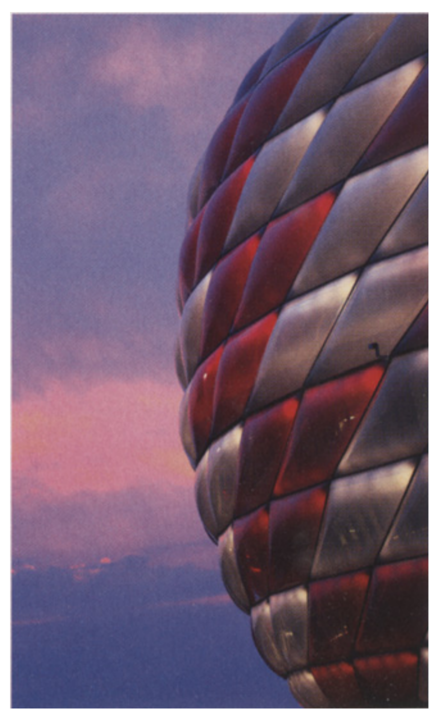

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Allianz Arena, Fröttmaning, Munich
Herzog & de Meuron, 2005 /
4–7__Programmed lights with colored lenses behind the translucent printed cushions activate the skin, making the stadium highly visible from the autobahn and rousing spectators as they approach the stadium on foot. /

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8__Self-draining metal tubes are incorporated in the roof cushions to assist with heavy rain and snow loads. /
9__A concealed perimeter gutter subtly separates the cladding systems for wall and roof. /
10__Although the cushion pattern appears to be repetitive, there are 1392 different rhomboid components. /

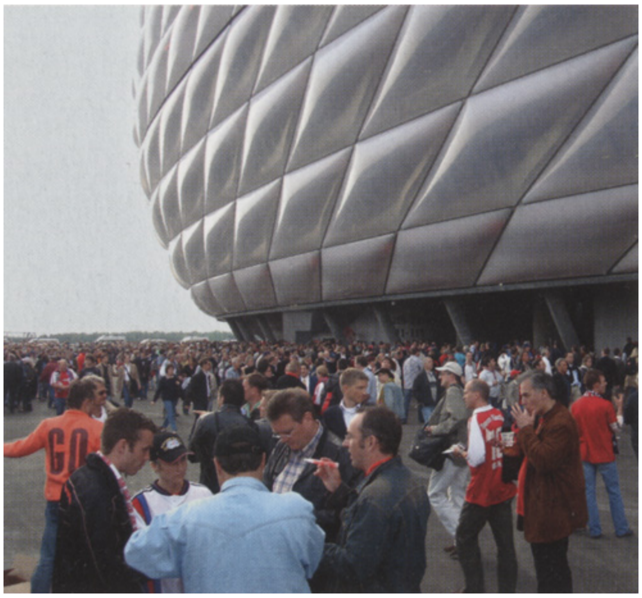
long radial roof girders, which are steel trusses with parabolic upper and lower chords.

The ETFE cushion skin wraps both the enclosing wall and roof of the stadium, negotiating seemingly effortlessly between the concrete and steel primary structures. Although ETFE cushion systems typically eliminate the need for secondary structure, the large scale of the stadium required separate steel framing to support the cladding. This grid, which curves in two directions, is connected to the primary structure by short hinged columns and spring torsion bars that both allow and limit deformation. While the skin looks continuous, there are two discrete support structures for wall and roof, which are separated by a concealed perimeter gutter.

Likewise, the gutter at the inner edge of the roof is masked by a pneumatic fascia. Although the pattern of the 2784 ETFE cladding panels appears to be repetitive, the complex geometry of the stadium's curvature produced 1392 different rhomboid components. The cushions range from 2 x 7 meters to 5 x 17 meters, with side lengths of 4–8 meters. The stadium is divided into eight segments that are structurally independent from foundation to roof. To allow for thermal movement in the ETFE envelope without continuous expansion joints that would interrupt its homogeneous appearance, multiple local hinges in the plane of the horizontal framing components between cushions absorb expansion and help to prevent folds in the membrane.[2]

The performance of the Allianz cushion envelope has been adversely affected by technical issues, including failure of some cushions because of the design of the bespoke edge extrusion and difficulties with snow loads on this extensive low slope roof. To deal with heavy loads, pressure in the roof cushions, normally 300 Pa, can be increased to 800 Pa. In addition, 1900 roof cushions incorporate a self-draining metal tube that moves up and down under variable loading, sliding through an O-ring in the inner layer of foil. However, air loss around the ring leads to low inflation, which can exacerbate the tendency of the cushions to deflate, invert, pond and fail under heavy rain and snow conditions.

The two layer wall cushions are printed with a variable white dot screen, which is more dense at lower levels to prevent the illuminated skin from blinding drivers on the



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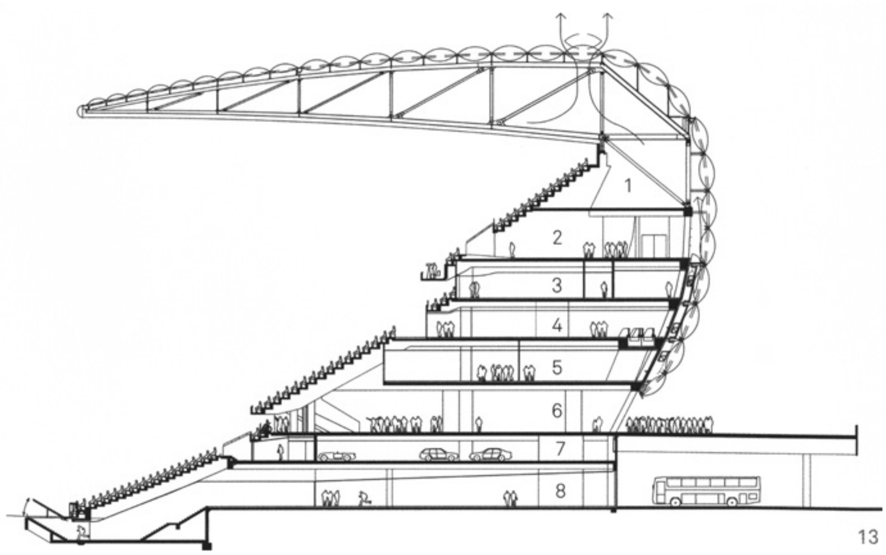

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11–12__Building on the sense of expectation developed externally, the design of the tiered seating and retractable roof screening create an intense spectator atmosphere within the stadium. /
13__Section through west stand
1 services
2 small promenade
3 boxes
4 business club
5 sponsors' lounges
6 grand promenade
7 VIP parking
8 players' tunnel /

autobahn. The roof cushions, also two layers, are clear over part of the area to enable sunlight to reach the grass of the pitch. On the underside of the roof girders, a retractable mesh of polyurethane and fiberglass provides shading for spectator comfort on sunny days and, like a cloud, veils the primary structure, enabling spectators to focus on the match.

The most compelling aspect of the arena's lightweight building envelope is its lighting. When illuminated, the ETFE cushions are transformed into an active and sensual skin that, in addition to providing protection from the elements, entertains passing traffic and builds up the spirits of supporters approaching the stadium. Standard fluorescent tubes fitted with red, blue and white lenses are programmed to project animated sequences of colors of the teams who use the stadium. Specially designed parabolic reflectors ensure even light distribution, and the 25,500 fittings can be maintained from traveling gantries on the inner face of the envelope. In addition to its entertainment value, the fire performance of this ETFE envelope and its lighting result in a very low fire load for the stadium.

Graphics

Projected and programmable lighting also animates the Beijing Water Cube, making the building itself, as much as the swimming competitions within, one of the spectator events of the 2008 Olympics. This strategy has been further developed at Saint Jacob Stadium in Basel, where the original 1960s polycarbonate skin has been recently replaced with an ETFE cushion system. A steel grid clipped onto the stadium's concrete superstructure supports 3.5 meter high by 25 meter long cushions that, alongside roads and rail lines, emphasize the dominant horizontality of the site. This new skin, completed in 2006 to provide weather protection in the spectator zones beneath the stadium rake, also advertises and entertains. In addition to changeable colored backlighting, the outer foil of the two layer cushions features 12 meter high lettering that operates at the scale of the surrounding infrastructure. Instead of printing or merely applying an extra layer of foil to the surface, the white foil is cut away and replaced with red, so that the lettering is literally embedded in the skin. Complex patterning, cutting and welding of the letters into the variable curved surfaces create a crisp appearance

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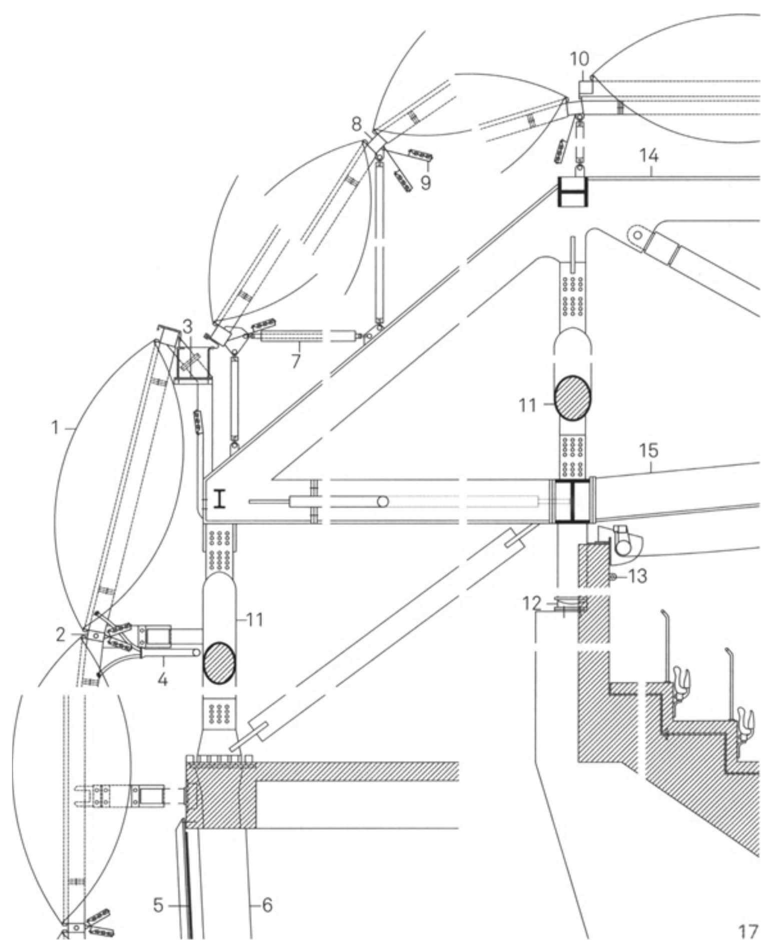

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14__Full-scale mock-ups were used to test and refine cladding details. /
15__The stadium superstructure combines concrete seating tiers and trussed steel roof girders. /
16__Cascading precast concrete stairs around the perimeter help to brace the double-curved structure. /
17__Section through roof over west stand
1 pneumatic element with 0.2 mm white ETFE
2 polyolefin seal on 120/220 mm steel RHS
3 rainwater gutter
4 Ø100 mm air-supply tube to pneumatic element
5 galvanized steel protective grating
6 reinforced concrete composite column of variable diameter
7 Ø140 mm tubular spring unit
8 polyolefin seal on 180/180 mm steel SHS
9 three color façade lighting
10 operable ETFE pneumatic ventilation element
11 tubular reinforced concrete composite diagonal bracing
12 ball bearing
13 fluorescent tube
14 Ø600/600–300/200 mm welded steel box girder
15 Ø600/460–300/200 mm welded steel box girder /

18

Saint Jacob Stadium, Basel
Herzog & de Meuron, 2006 /
18__Lettering, literally embedded in the skin, required complex patterning, cutting and welding. /

without distortion, bubbles or wrinkles when the cushions are inflated and illuminated. The foils were specially patterned using non-linear load analysis to enable the different moduli of elasticity of the foils to be carefully coordinated to ensure equal stress under all load conditions. Both patterning and welding required special machinery to achieve the complex three-dimensional curves and welds. This combination of fixed supergraphics and programmable lighting adds a new dimension to the communicative potential of ETFE cushion envelopes.

A further strand of research exploring the migration of services onto the surface is the work being done at Vector Foiltec to integrate light tapes and LED's into cushion assemblies. In addition to the projected and reflected lighting effects achieved by placing conventional light fittings and colored lenses behind cushions, this technology offers the potential of light sources on the surfaces of the foils that can be programmed to perform on demand, transforming the building envelope into a multi-dimensional pixilated skin. In ways that Marshall McLuhan could not have imagined, material – in this case ETFE and air, or almost nothing – is infused with media to literally become the message.

1__ Sheila Kennedy. "Material Presence: The Return of the Real," Material Misuse (London: AA Publications, 2001), p. 9.
2__ Rudolf Findeiß, Johann Pravida and Kurt Stepan. "The Steel Construction – the Roof Structure and Vertical Façade," *DETAIL* (No. 9, 2005) p. 965.

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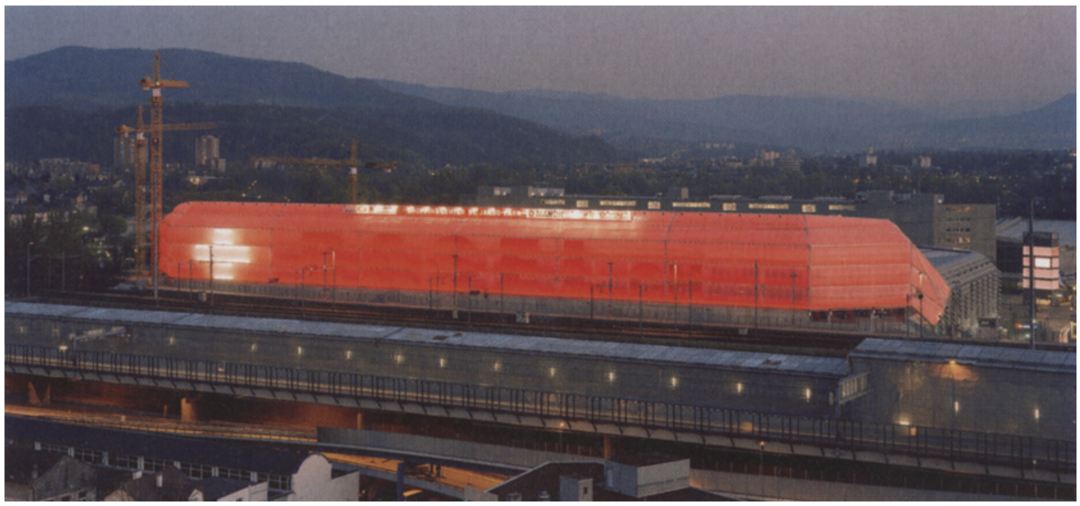

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19–21__Fixed supergraphics and programmable lighting expand the ETFE envelope's communicative potential. /

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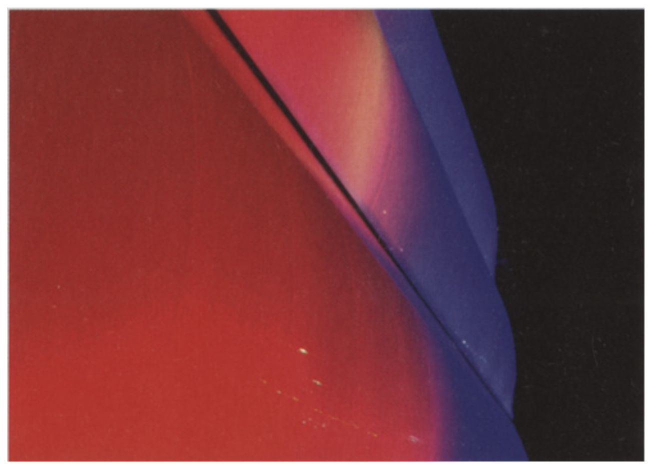

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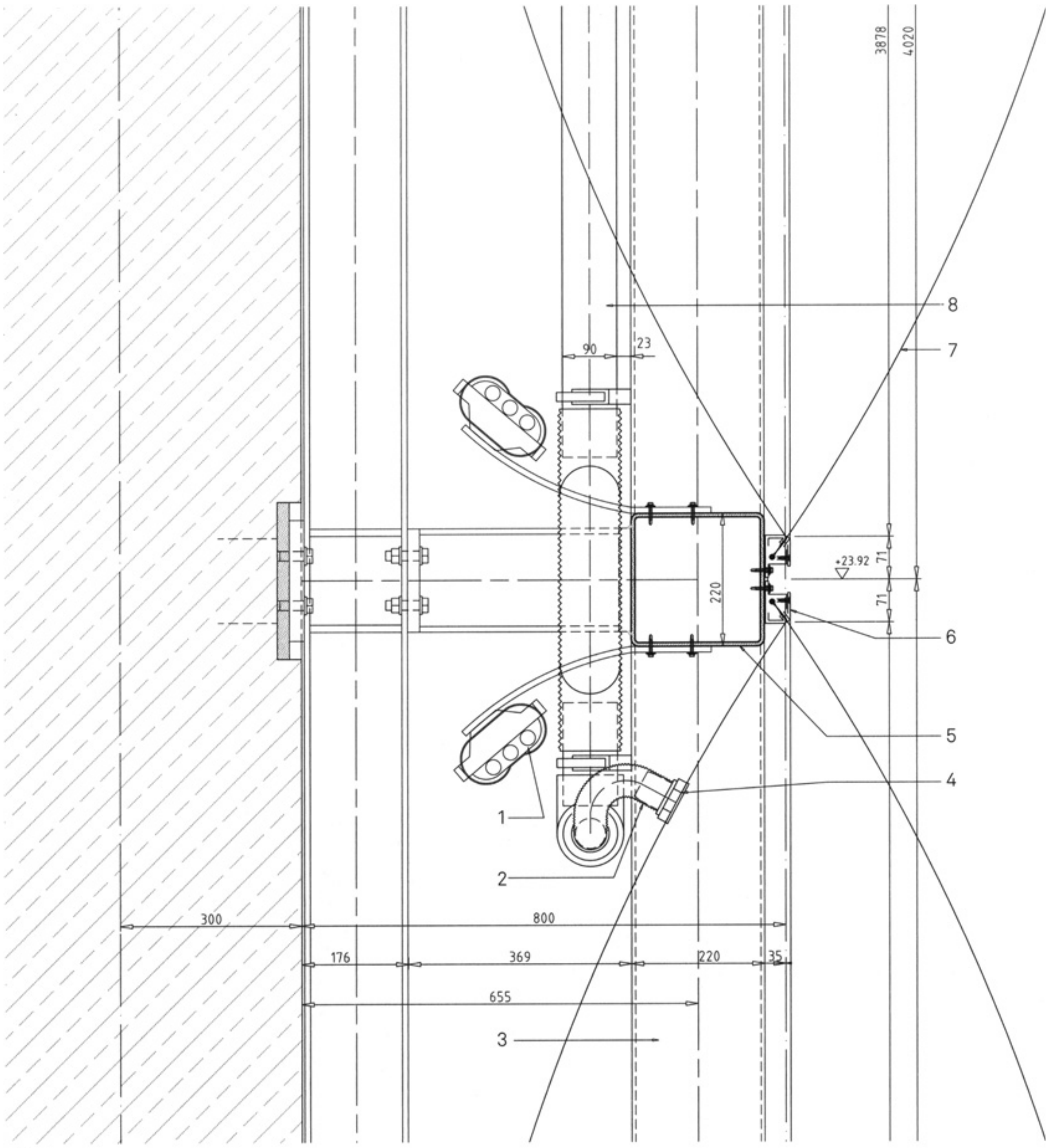
22–26_The embedded lettering operates at the scale of surrounding urban infrastructure. /



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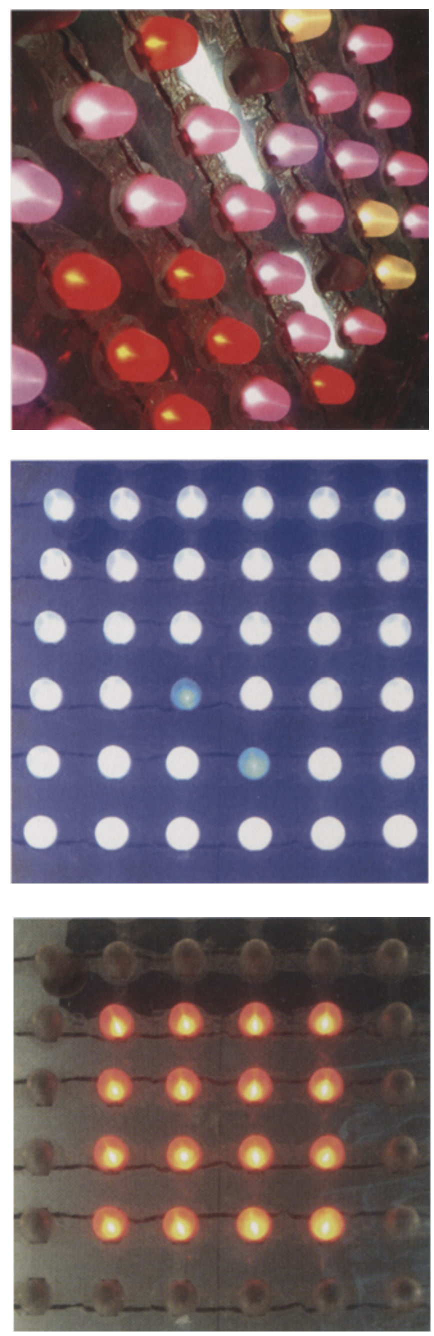
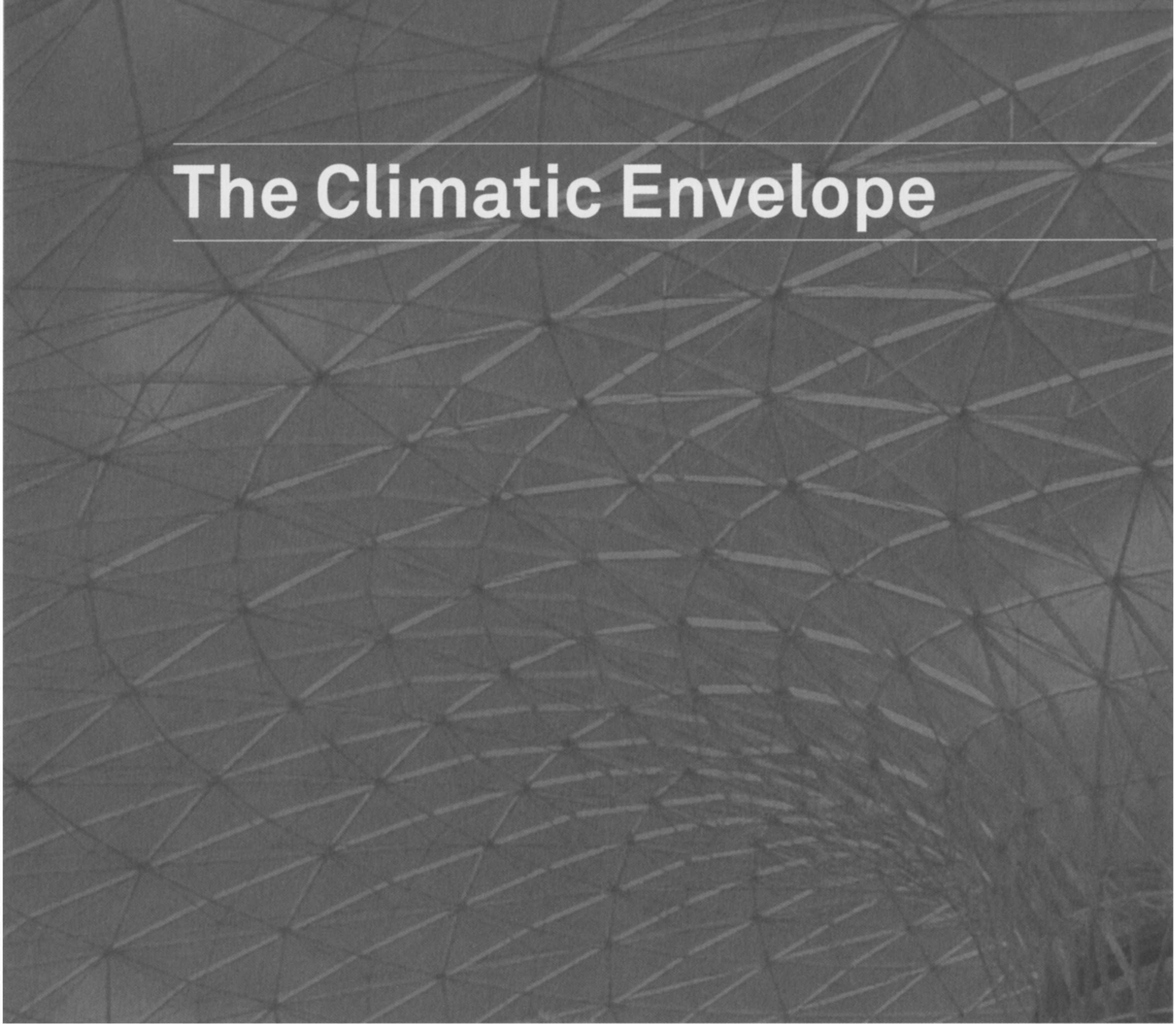


28–30

27__Detail façade section
1 LED façade lighting
2 wire stabilized hose Ø 50 mm
3 vertical steel section
4 cushion valve Ø 50 mm
5 horizontal steel section
6 aluminium cushion edge extrusion
7 two layer ETFE cushion
8 air supply PVC tube Ø 90 mm /
28–30__Mock-ups explore the integration of LEDs into ETFE cushion assemblies. /

The Climatic Envelope



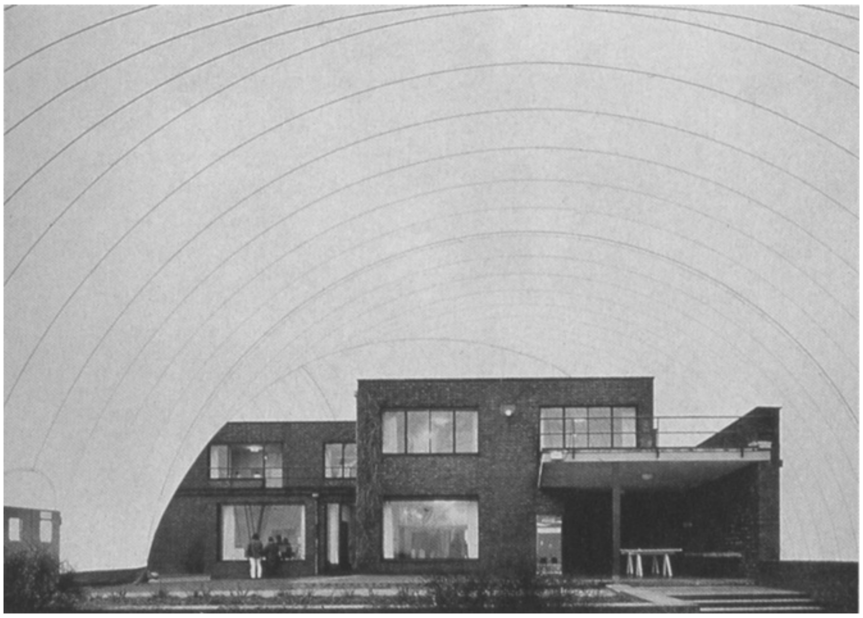
From its arrival in the market place in the 1970s and the early building envelopes that followed, ETFE has moved from being an alternative material at the periphery of architectural interests into the mainstream, and from the realm of pleasure to precincts of power. A key factor in this evolution has been the integration of ETFE and air in cushion enclosure systems. From the early plant houses, swimming pool enclosures and temporary exhibition pavilions, ETFE cushion envelopes have been developed for a widening range of institutional applications including health care facilities, government buildings, museums and transport infrastructure. In addition, this lightweight fluoropolymer has proved to be as useful in the regeneration of old buildings and cities as for the construction of new ones. While early ETFE clad buildings were located in temperate regions, recent projects are testing the performance of this enclosure system in more hostile environments.

The trajectory

As well as a broadening range of typological and climatic applications, ETFE cushion enclosures have grown significantly in size. Though not yet of the scale of the city, as imagined in the Manhattan Bubble and 58 Degrees North, the latest ETFE projects mark a shift from individual buildings to the larger scale of what Frei Otto called "non-buildings" – vast climatic envelopes sheltering multiple buildings with extensive landscapes, all within a single enclosure. These enveloped landscapes blur the distinction between interior and exterior and, importantly, function not only as pleasure gardens, but also as essential components of environmental servicing strategies that reduce energy consumption and reliance on mechanical systems.

A pessimistic view

The idea of the climatic envelope, or environment bubble, which shaped conceptions of paradise, has also been driven by the needs of human beings living in harsh environments in the Sahara, the Arctic or outer space. However, as visions of paradise make clear, idyllic conditions within are only understood relative to less-than-ideal circumstances beyond the bounds. The problem of the bounded domain – whether the Garden of Eden, the island of Utopia or the climatic envelope – is that, unlike the democratic spectacle of Montgolfier's balloon, occupation within is



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1–2__In 1971, Haus Rucker Co. wrapped Mies van der Rohe's Haus Lange in an air-supported bubble to focus attention on the perils of environmental pollution. /

selective and controlled. Notwithstanding its attributes, the environment bubble, like a gated community or private sky,[1] raises issues of the co-opting of the public domain by private interests.

The climatic envelope is not unique in this regard, as all technologies pose risks and offer rewards. Buckminster Fuller optimistically proposed environmental bubbles while highlighting the delicate balance between Utopia and oblivion. Likewise, just as the collection of air-supported architecture at Expo 70 in Osaka conjured the best of all possible worlds, another pneumatic installation at about the same time in Germany projected a more pessimistic view. In 1971, Haus Rucker Co. encapsulated Mies van der Rohe's Haus Lange in Krefeld in an air-supported envelope. The installation, called "Cover – survival in a polluted environment," was forebodingly described in the exhibition's catalogue: "Cities are buried under coverings of smog. The dust that is swallowed by the inhabitants of these cities can be measured in lorry loads. The streets have changed into gas chambers, the rivers into viscous poison brews... 'Cover' makes a jump in time and shows the situation that will arise if increasing contamination of the environment continues: life in artificial reservations...[At Haus Lange] a climatic 'island' is created which, equipped with the necessary technical apparatus, becomes a self-sufficient life cell...A small synthetic cosmos surrounds the house from which it is impossible to break out. Noah's ark is launched again."[2]

This kind of environmental doom-mongering, which might have been dismissed as extremist at the time, is now being taken more seriously. The climatic island dscribed by Haus Rucker Co., much like Reyner Banham's highly serviced environment bubble, was a provocative and polemic transformation of the hermetically sealed and energy-intensive buildings that defined the second half of the 20th century. However, with increasing awareness that energy consumption by human beings and their buildings, in addition to depleting natural resources, is causing and accelerating climate change, the idea of the climatic envelope is now fueled by an increasingly urgent quest for environmental sustainability.

Optimistic views

Current ETFE projects illustrate a wide spectrum of

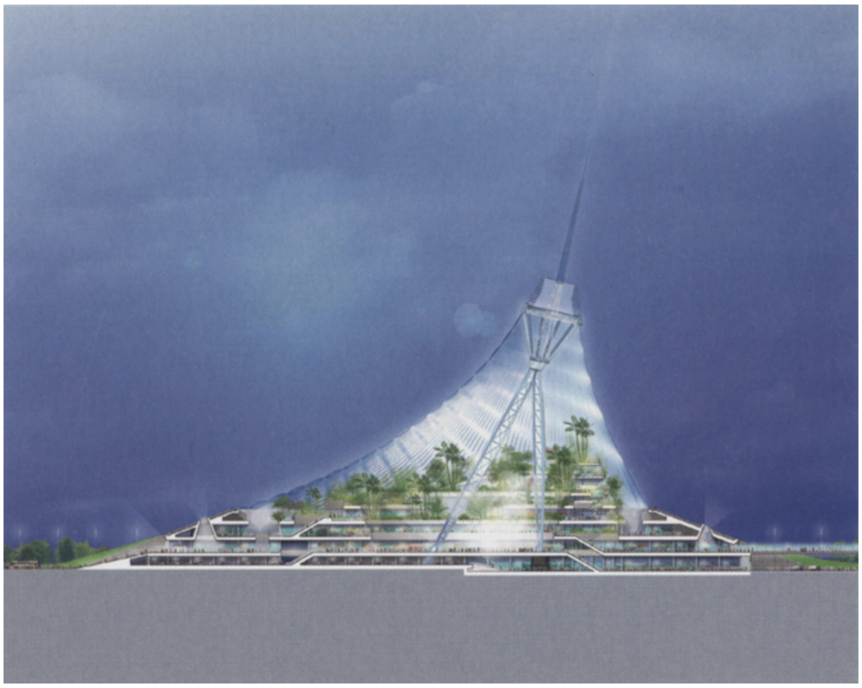
3

Khan Shatyry Entertainment Center, Astana
Foster and Partners, 2008 /
3–4__An ETFE cushion climatic envelope encloses multiple buildings and an urban-scale tropical landscape. /
5__Cable detail from below /
6__Radial cables of the mast-supported cable net resist positive wind pressure, while circumferential cables resist suction. Plan, isometric, side and front elevation of cable net /

approaches to issues of sustainability. The concept of the climatic envelope is being actively pursued in the construction of the Khan Shatyry Entertainment Center in Astana, the new capital of Kazakhstan. Like Brazilia, the city of Astana is being constructed from scratch. It is situated in an austere landscape with a harsh climate of severe weather and temperatures that range between +/- 35 degrees Celsius. Bringing to mind Frei Otto's preoccupation with the creation of paradisiacal environments in extreme climates, the aim of the Entertainment Center is to create a "world within" that offers a comfortable microclimate and lush landscape.

The complex, which is enclosed within a cable net structure clad with ETFE cushions, includes 100,000 square meters of retail, restaurants, entertainment venues and parking, together with stepped planted roofs that create an urban-scale tropical park replete with boating lakes and rivers. The asymmetrical anticlastic conical form of the biaxial cable net is supported at its apex by a 20 meter high inverted cone that is balanced on a 70 meter tall tripod mast. The cigar-shaped legs of the tripod comprise 1 meter diameter fabricated steel tubes. The cone, hinged to enable it to move with the tensile structure, carries 190 paired 32 millimeter diameter radial steel cables, that resist positive wind pressure, while circumferential hoop cables resist suction. The net is anchored to the ground by a perimeter concrete ring beam, which encloses a space that is 115 meters wide and 145 meters long. The plan form of the cable net is defined by four arcs with different centers.

The flexible ETFE cushion envelope is well suited to deal with the cable net's designed range of movement of approximately +/- 1 meter. In this geometrical configuration, as the structure deflects, the cables move closer together and the cushions change from their normal eye shape to become more cylindrical. To permit this to work effectively, continuous cushion edge extrusions parallel to the hoop cables, which would have created rigid collars, had to be avoided. Instead, alternating circumferential cushion joints enable the entire envelope to move like a concertina. Formidable snow loads of up to 7 metric tonnes per square meter are handled by stainless steel cables on the underside of the cushions. A key consideration in the design is to keep the variable slope of the cable net



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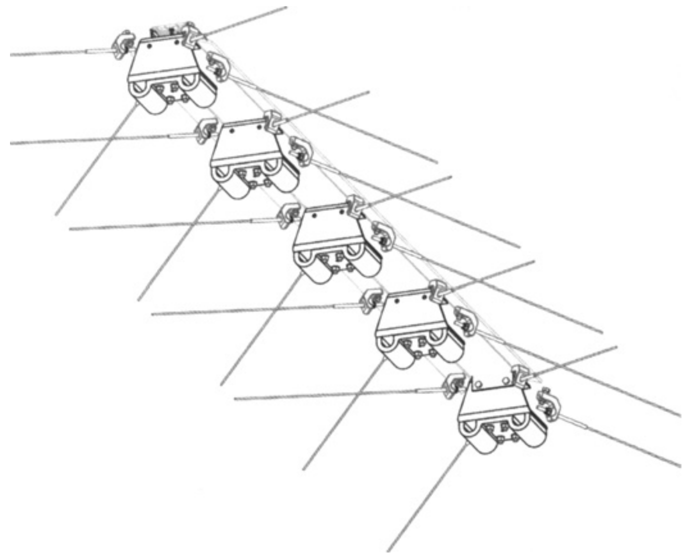

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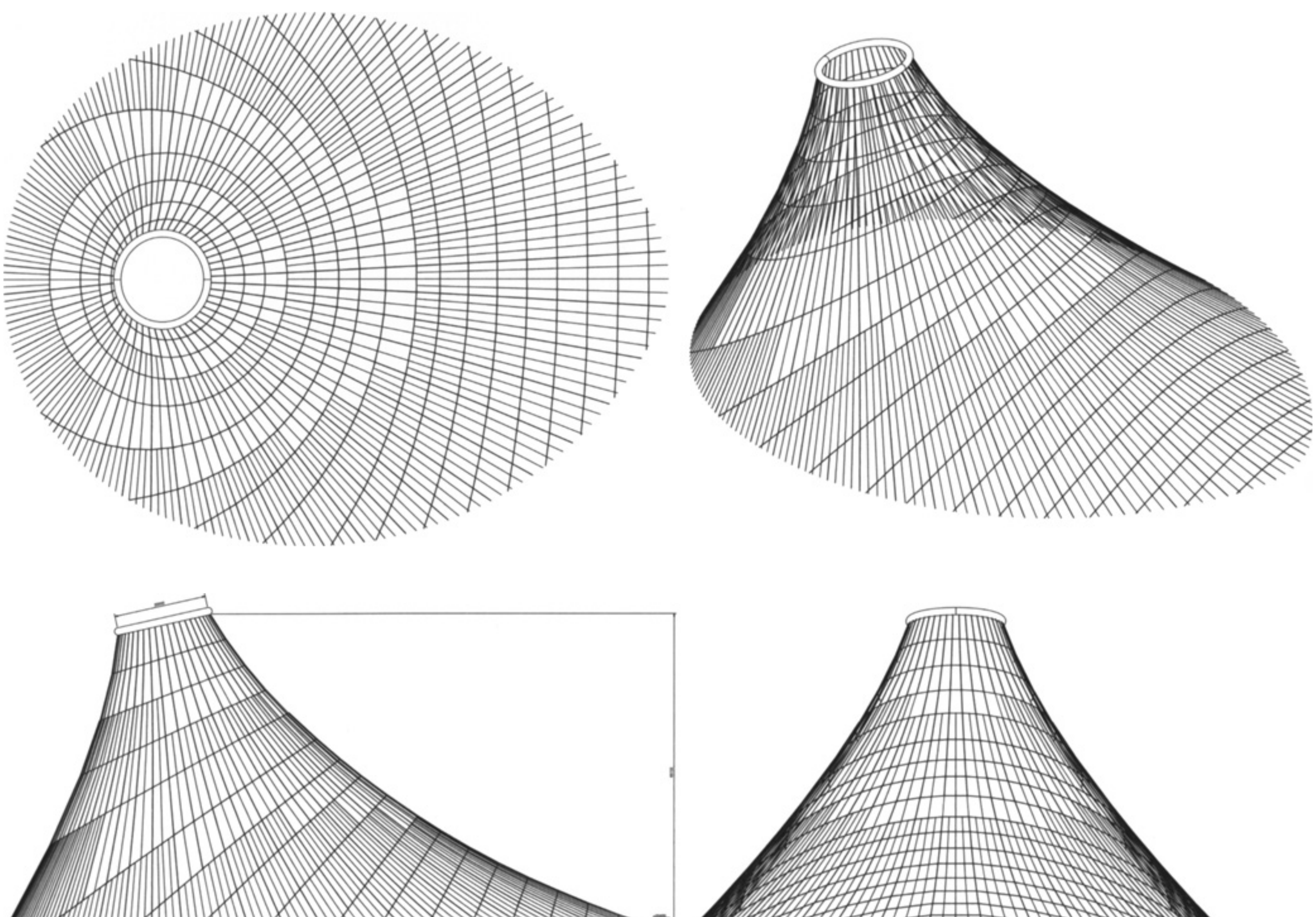

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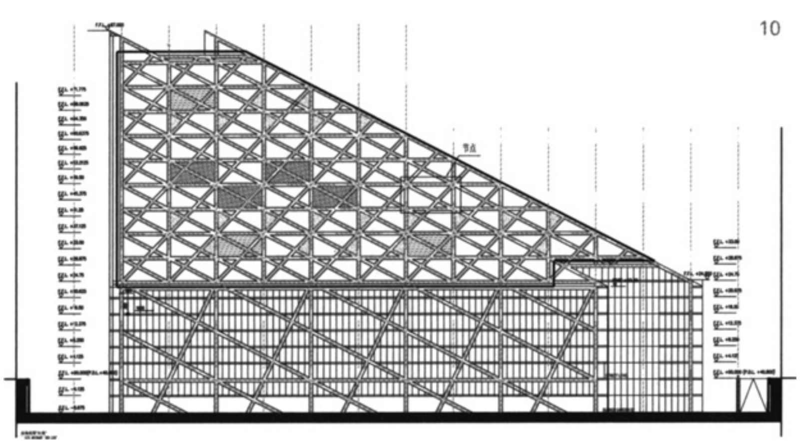


Parkview Green Plaza, Beijing
Integrated Design Associates, 2008 /
7–9__The climatic envelope, which wraps a group of buildings and is supported by extensive landscape inside and out, creates a refuge from Beijing's polluted environment. /
10__North elevation /

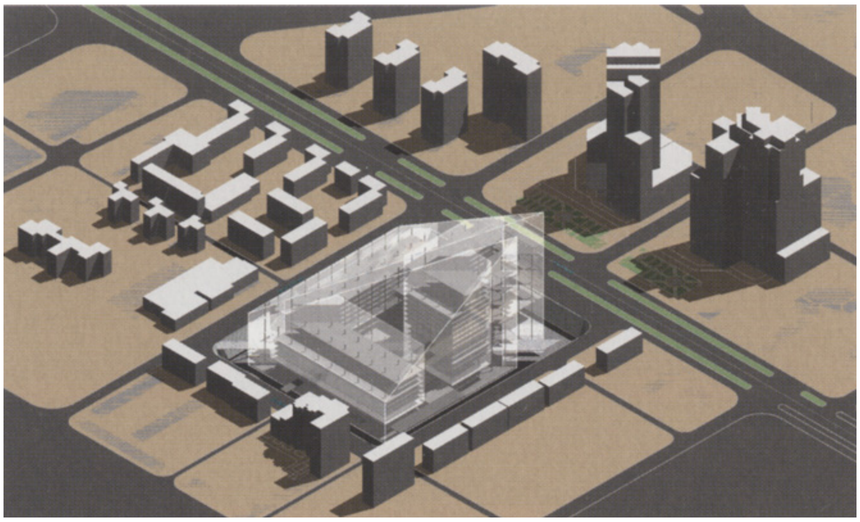
11__The ETFE cushion roof, less costly than glazing, supports an environmental strategy that combines passive and mechanical systems, aiming to minimize the scheme's carbon footprint. /

steep enough to allow rain and snow to run off the surface without forming ponds.

While the buildings within the envelope are fully conditioned, the environmental design target for the landscaped areas within the enclosure is a temperature of +15 degrees Celsius in winter and +30 degrees in summer. In winter, a key challenge given the cold, dry climate and the warm and moist interior microclimate, is to prevent the formation of ice on the three layer ETFE cushions. This is achieved by a combination of temperature control and blasting warm air from low level up the inner surface of the cushions. This strategy also helps to prevent strong downdrafts that are a natural consequence of the building's form. In summer, printing on the outermost foil layer provides solar shading. The same low level jets supply cool air, now directed across the space, and together with opening vents at the apex, induce natural stack effect ventilation. While the Entertainment Center requires substantial energy to maintain its lush landscape and benevolent microclimate, the design team has sought to mitigate energy input by combined heating and power, which uses waste heat from electricity generation for both heating and cooling.

Beijing also has a tough environment, which is a by-product of climate and culture. As a focus of China's rapid economic development, the city suffers from serious environmental problems like those envisioned by Haus Rucker Co., including water shortages and very high levels of air and noise pollution. Parkview Green Plaza responds to this adverse setting with a climatic envelope that creates a healthy micro-environment for the buildings and people sheltered within. Instead of being energy-intensive, it seeks to minimize its carbon footprint by incorporating sustainable materials and passive servicing strategies.

The site, east of Tiananmen Square, is a full urban block on the boundary between low rise diplomatic compounds and residential areas and high rise office towers to the east. Planned with five basement retail and parking levels, and rising from five floors above grade on the north and west sides of the block to 17 stories on the south and east, the four office buildings within the larger enclosure are designed so that they do not cast shadows on their neighbors. The resulting wedge-shaped section also induces stack effect ventilation. In addition to avenues of trees at ground level, the building is set back from surrounding



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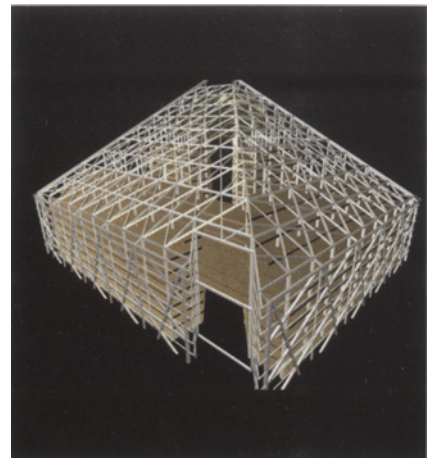

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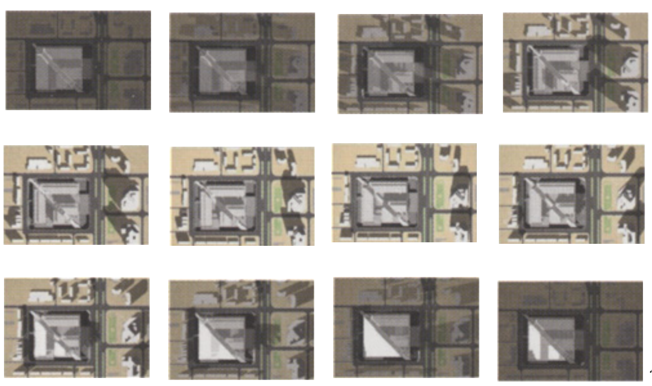

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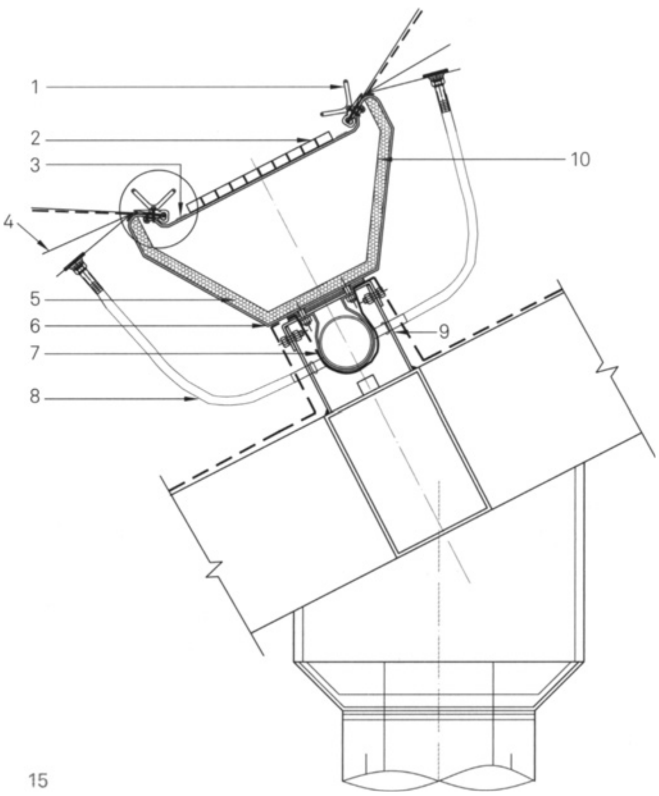
12–14__The envelope is designed to minimize shadows and create an environmental enclosure for the buildings. /
15__Detail gutter section
1 bird wire
2 galvanized steel plate
3 lightning tape
4 three layer cushion
5 insulation
6 painted steel gutter
7 galvanized steel pipe up to Ø 150 mm
8 Texlon ETFE pipe
9 steel bracket
10 PVC water proofing /

streets by a 24 meter wide, two story deep "moat" around the entire site, which provides building security and brings daylight to accommodation below grade. Designed as a sunken garden, the moat is planted with mature evergreen trees that filter external air near the low level intakes for the development. At ground level, entrance lobbies are reached via bridges and a diagonal public pedestrian route through the site is flanked by restaurants and retail, cultural and recreational facilities.

The outer envelope provides weather protection and creates a thermal insulation layer of air around the buildings. Its walls are single glazed with areas of operable glass louvers, and the sloped roof comprises three layer printed ETFE cushions. The inner building façades are therefore not classified as external walls, with considerable cost savings arising from their less stringent performance specification for weather-tightness. Within the outer envelope, all covered areas between buildings are urban public spaces that feature a reflecting pool to aid evaporative cooling and generous indoor planting, which assists with oxygen recovery. In addition to occupying the ground, the landscape extends vertically to provide amenity areas for office workers on terraces and bridges as well as accessible roof gardens for the luxury hotel that is situated on the top floors of the complex. With ample planting both inside and out, over 40 percent of the site footprint is green space, providing a publicly accessible oasis that offers respite from the rigors of the Beijing environment.

The scheme's environmental strategy is a hybrid of passive and mechanical systems. To cope with external temperatures that range from -20 to +40 degrees Celsius, the individual buildings are fully conditioned by means of underfloor air conditioning with chilled ceilings. At ground level in the interior public zones, the target summer temperature is 25 degrees Celsius, approximately 8–10 degrees lower than typical external temperatures. This is achieved by controlled leakage of cooling from the buildings combined with evaporative cooling and natural ventilation through openings in the outer envelope just above the lower buildings and at the apex of the wedge. In winter, to achieve a target interior temperature of 5–10 degrees Celsius, some 10 degrees warmer than average ambient temperatures, the external envelope is open only at the base, and the fresh air admitted is heated by the sun and



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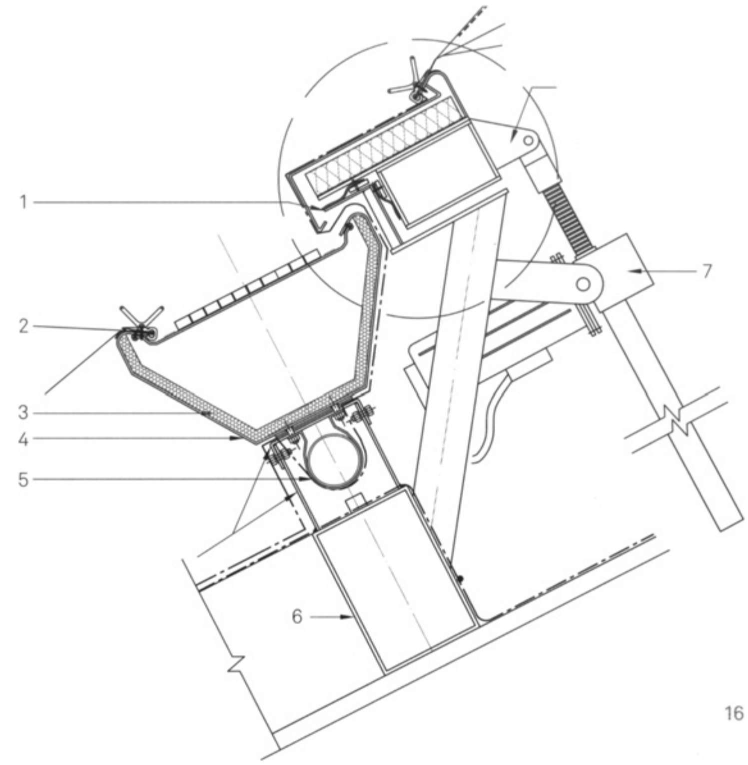


16

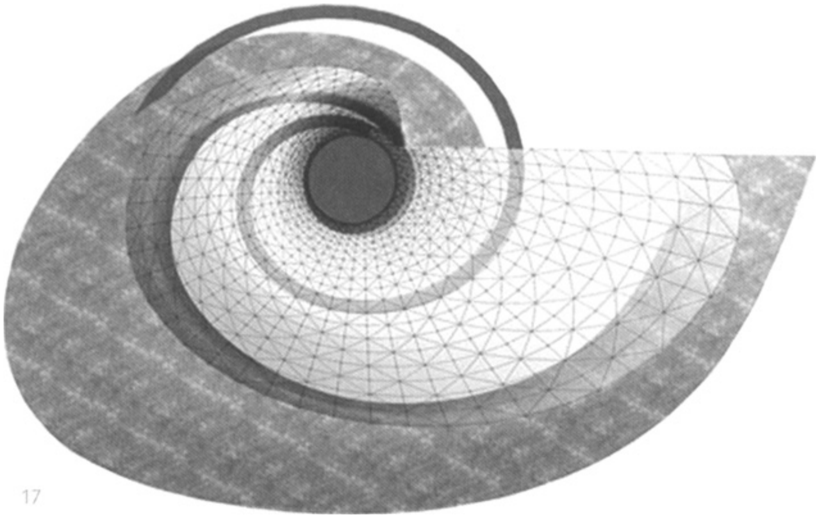
16___Screw jack detail
1 Z-section 6 mm gasket
2 three layer cushion
3 insulation
4 painted steel gutter
5 galvanized steel pipe up to Ø 150 mm
6 U-section 300 x 300 x 10 mm @ 750 mm centers
7 screw jack mechanism /

by leakage from the buildings. The energy demand is lowest in spring and autumn, when both interior and exterior temperatures are approximately 20 degrees Celsius, so that both the outer envelope and inner buildings may be open and all areas naturally ventilated.

The ETFE roof supports this environmental strategy, providing thermal insulation and balancing the needs for ample daylight for the interior planting with solar shading for the comfort of human beings. The scheme also benefits from ETFE's soft structural behavior in this active seismic zone. The public areas, although enclosed by the environmental envelope, are classified as open space as a result of extensive fire engineering to satisfy stringent local codes. Finally, the lightweight ETFE cushion envelope and its supporting structure are considerably less costly than an equivalent glazed roof.

The ideal of the garden paradise, which clearly inspired the Eden Project, is being further developed at Earthpark in Iowa, where tropical biomes are being created in a more difficult climate defined by hot summers and cold, snowy winters. Importantly, this scheme aims to be carbon neutral. This development will feature a 1.6 hectare (4 acre) structure, slightly larger than Eden's Humid Tropics Biome, which will enclose three Amazonian regions: the deep jungle, the cloud forest and the flooded forest, which includes a 2.27 million liter aquarium. Within the nautilus-like form of the enclosure, these distinct regions wrap a central six story core that houses visitor interpretation facilities and the life support systems for the aquarium. The form naturally accommodates both the flooded forest, which is low and expansive in area, and the cloud forest, which requires a 50 meter high space.

The design of the enclosure must maximize daylight to support the tropical biomes and to compensate for a frequently overcast sky in Iowa. All biomes will benefit from southern exposure, and the flat north edge of the form is dug into the ground so that the rock face can be used as a heat sink to capture solar gain. The proposed structure, which aims to be lighter than the double layer geodesic structure of the Eden Project, is a triangulated grid shell of steel tubes that is stiffened internally by a three-dimensional cable truss. The ETFE cushions will be limited to three layers, as additional load sharing foil layers would diminish light transmission. In addition to maximizing



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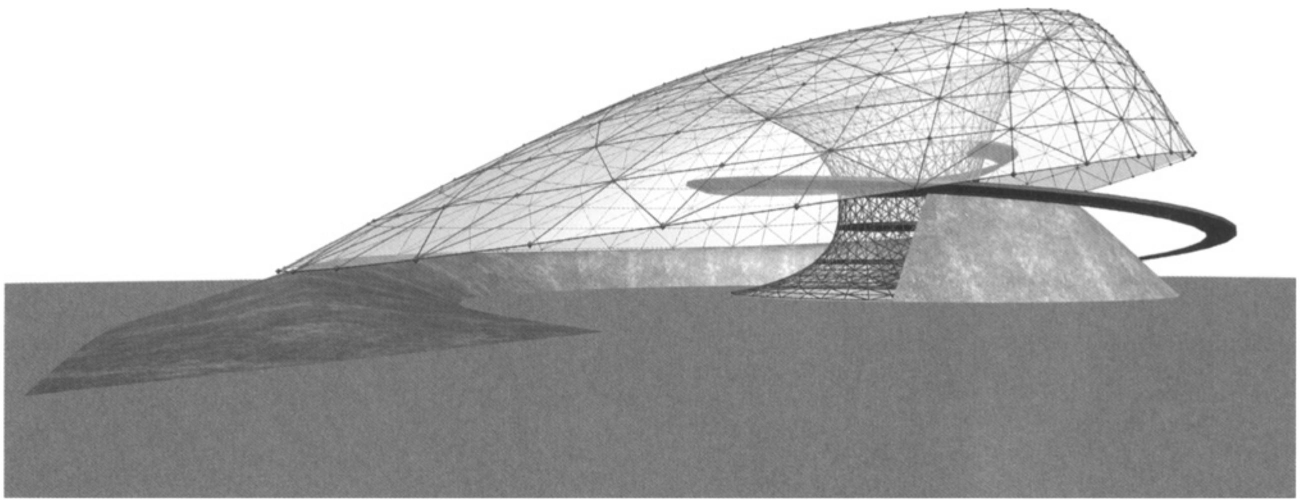


daylight and utilizing natural ventilation, other sustainable strategies include rainwater harvesting and graywater recycling. Approximately 20 percent of the energy for the development will be generated on-site by new ethanol-powered fuel cells, and 80 percent will be supplied by a wind farm that is being constructed off-site.

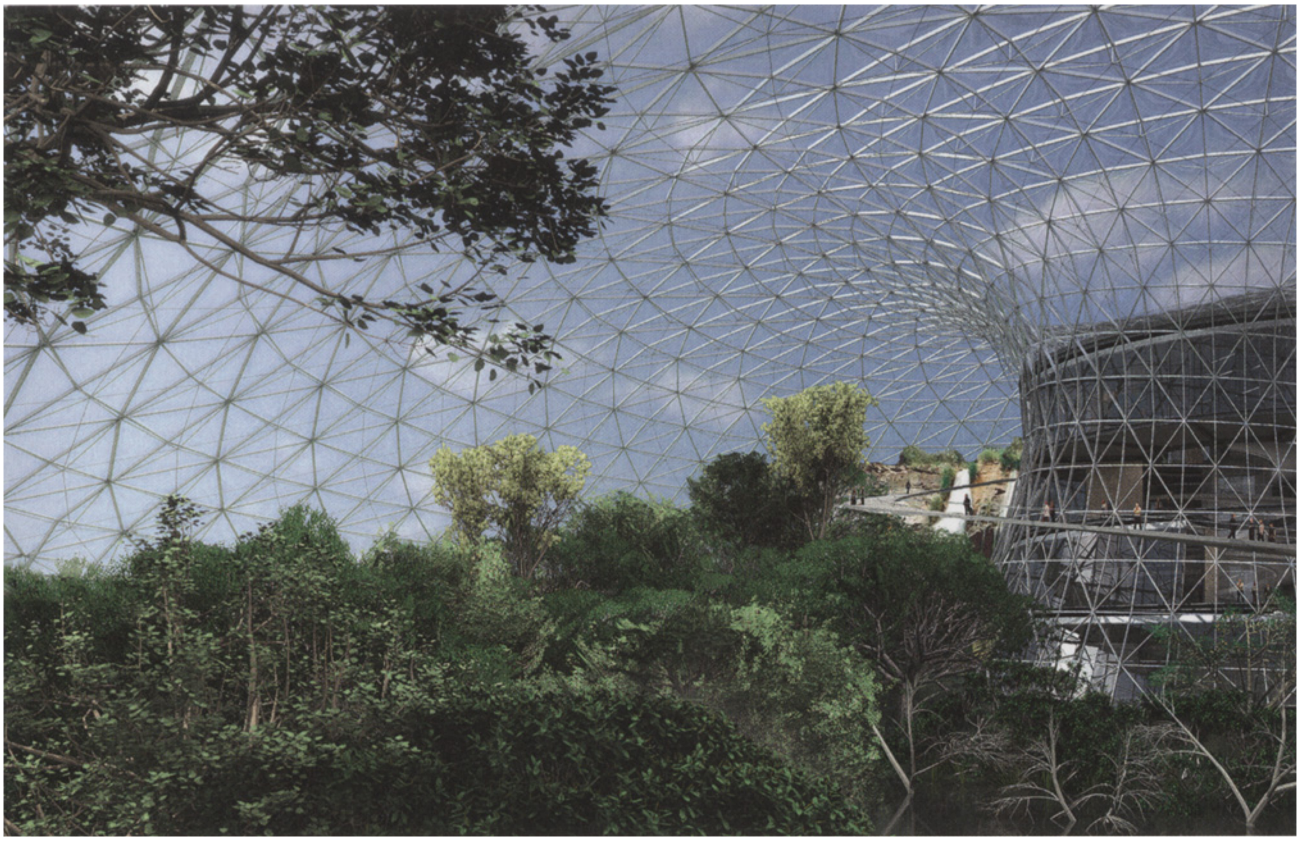
This project reflects a shift of emphasis in Iowa's agricultural economy from growing crops for food to investing heavily in ethanol and other forms of biofuel. It is noteworthy that although the US Republican administration has been slow to address or even acknowledge issues of climate change and environmental sustainability, Earthpark is being supported by a grant from the US Department of Energy and, in addition to being a major national public attraction, will be the focus of a research park for the US Green Building Council, Siemens and other environmentally focused agencies and businesses.

A sustainable view

The understanding of lightness, focused during the 20th century on the development of lightweight structures and enclosures, is now being amplified by the need to reduce energy and resource consumption. Payload, critical in the weightless environment of space, is now even more important on the ground, where its most compelling unit of measure is carbon units. Individuals, businesses, industries and governments are increasingly engaged in efforts to reduce, or lighten, their carbon footprints.

Fortuitously, ETFE earns high marks as a sustainable material and its harnessing of air – ubiquitous, free and recyclable – is producing a new genre of very lightweight and dynamic building envelopes that are highly effective environmental modulators. It has been argued that all architecture is motivated by the desire of human beings to shelter from the vagaries of nature. Alvar Aalto nobly expressed this sentiment when he observed, "Architecture... has an ulterior motive...the idea of creating paradise. Every building is intended to show that we wish to build a paradise on earth for man."[3] Others more matter-of-factly suggest that buildings have historically been designed to compensate for inadequacies of human skin to provide protection from hostile environments.[4]

ETFE cushion systems combine minimal material and high performance to overcome these inadequacies



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Earthpark, Pella, Iowa
Grimshaw, 2010 /
17–18__A nautilus-shaped triangulated grid shell is to be stiffened by a three-dimensional cable truss. /
19__The 1.6 hectare enclosure, which will shelter three Amazonian biomes, is being designed to be carbon neutral. /

and move closer to the ideal. Instead of the sterile synthetic cosmos that was envisioned at Krefeld, this technology is proving to be environmentally responsible and respon-sive. Banham's environment bubble, occupied for a day and discarded, has matured and now boasts a host of long-life and sustainable attributes. The ability to vary light transmission, thermal and acoustic properties; to incorporate technology that can produce renewable energy; and to communicate and entertain transforms the building envelope – formerly essentially static – into an interactive and performative skin. ETFE cushion build-ing envelopes exemplify the dictum that efficiency ephemeralizes. Tethered to the earth lightly, they marry the pneumatic imagination with the quest for an ideal environment. Pleasure, power and payload are once again inextricably intertwined.

1__ The term "private sky" is from the book on the work of R. Buckminster Fuller edited by Joachim Krausse and Claude Lichtenstein, *Your Private Sky* (Baden: Lars Müller Publishers) 1999.

2__ Thomas Herzog. *Pneumatic Structures – A Handbook of Inflatable Architecture* (New York: Oxford University Press) 1976, p. 103.

3__ Juhani Pallasmaa and Peter MacKeith. "On History and Culture," *Architectural Record* (June 2007) p. 106.

4__ See Ellen Lupton's essay "Skin: New Design Organics," *Skin* (New York: Princeton Architectural Press) 2002, pp. 32–33.

Ben Morris

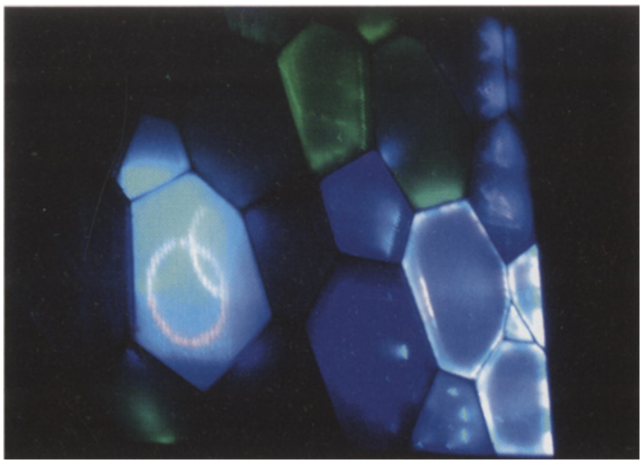
ETFE Futures

Ever since plate glass was invented in the late 18th century, humanity has been attempting to build ever lighter and more transparent spaces. These probably reached their zenith in buildings such as Paxton's Crystal Palace in England in 1851. The advent of patent glazing in the late 19th century made overhead glazing generally available. However it was not until the post war production of aluminium extrusions and the development of double glazing in the 1960s that glass could be used to cover and insulate the permanent building envelope. This gradually evolved into the building types that we know so well today, such as the lightwell as atrium or the street as shopping mall, where "public" external space has been incorporated into the "private" building envelope.

Twentieth century architectural visionaries such as Buckminster Fuller and Frei Otto made utopian proposals for enclosed and inhabited cities that would liberate the masses from the rigors of climate. Post war developments in plastics, particularly vinyl, polycarbonates and acrylics, enabled the early realization of some of these visions, but the technology lagged a long way behind with major failures due to thermal movement, fire and UV degradation.

ETFE was first investigated as a cladding material in the late 1970s; however, it was very difficult to process and the first usage of the material treated the foils as one layer stressed membranes limited by the roll size of some 1.5 meters in width. It was not until my partner Stefan Lehnert developed ways of welding these incredibly thin membranes together with a consistent quality of structural weld that did not compromise the strength of the parent material that the technology could develop. This seemingly easy task was not achieved by anyone else for some 20 years, and even today Vector Foiltec's welding technology is both unique and more reliable than any available on the market.

This expertise allowed us to grow the Vector Foiltec group and develop the technology with the support of innovative architects, engineers and clients. Following the building of Burgers' Zoo Mangrove Hall in 1982, ETFE technology was nurtured in aquatic and leisure buildings in Europe. Since these buildings are conceived as short-life projects, clients in this sector typically work on the basis of real estate pay back periods of ten years, which encourages the use of unproven solutions. These economic



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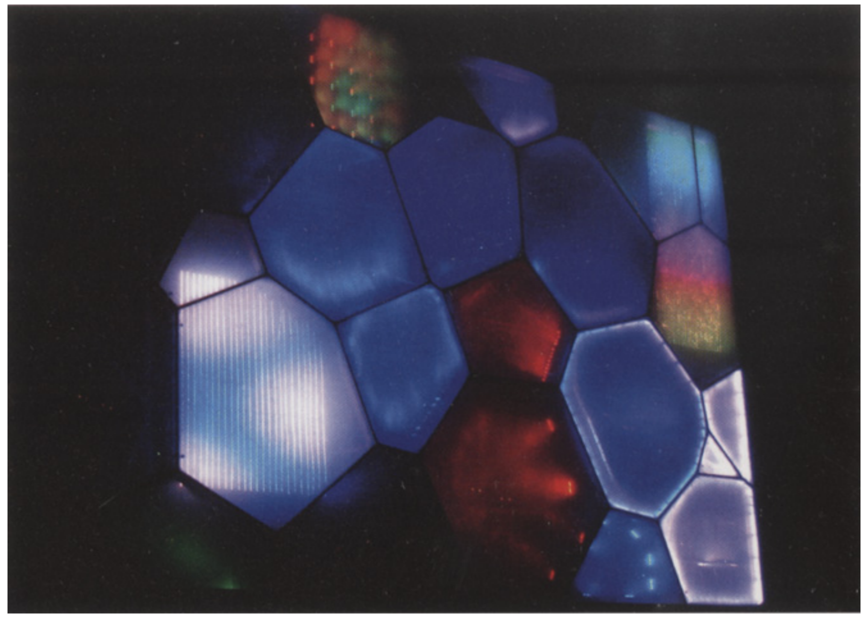


2

1–2__Programmable lighting test at the Water Cube in Beijing /

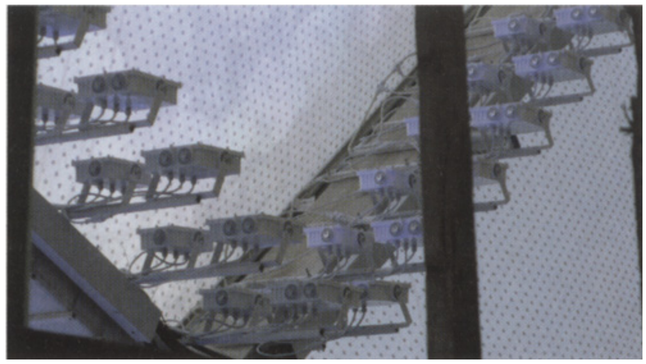
conditions promoted the adoption of innovative technical proposals for very complex buildings. These envelopes have to deal with high humidity and corrosive environments, and the use of solar gain is critical in offsetting heating costs. The good insulation properties, chemical stability and longevity of ETFE did much to prove its caliber and assisted its adoption by the wider architectural community.

This was evident when we roofed the London Chelsea and Westminster Hospital in 1990. The building was innovatively planned around a vast "cathedral-like" atrium that utilized the power of the sun to heat and cool the space and required the roof to act as a thermal duvet to ensure maximum heat retention. The technology was subsequently adopted and promoted by a number of architects in Europe, and we continued to develop and expand it to deal with new challenges. In 2001, the Vector Foiltec group built the Eden Project, which probably did more that any other scheme in catapulting ETFE onto the world stage.

Since then the technology has been adopted around the world and used across all building types, be they Paris fashion houses, government embassies, corporate atria or sports stadia. Over the last few years we have seen the first examples of Buckminster Fuller and Frei Otto visions being built. Buildings such as Parkview Green Plaza and the Water Cube in China and Foster's Khan Shatyry Entertainment Center in Astana are all examples of climatic envelopes enclosing a number of different buildings.

It is probably too early to assess whether ETFE is a passing fashion or whether it is a technology that has entered the architectural mainstream, and which in turn has and will have a profound effect on the development of architectural form. Ian Liddell, a key figure in the development of stressed membranes and ETFE foil cushion structures, has analyzed the rise and fall of architectural and structural technologies through recent history. He looked at concrete shells and space frames in the 1960s, the development of stressed membranes in the 1970s and the invention of ETFE in the 1980s and charted their movements as architectural fashion changes. It is yet undetermined whether ETFE will follow concrete shells and the like into architectural oblivion, or whether it will, like the curtain wall, become a dominant technology in the conception and cladding of buildings.

3



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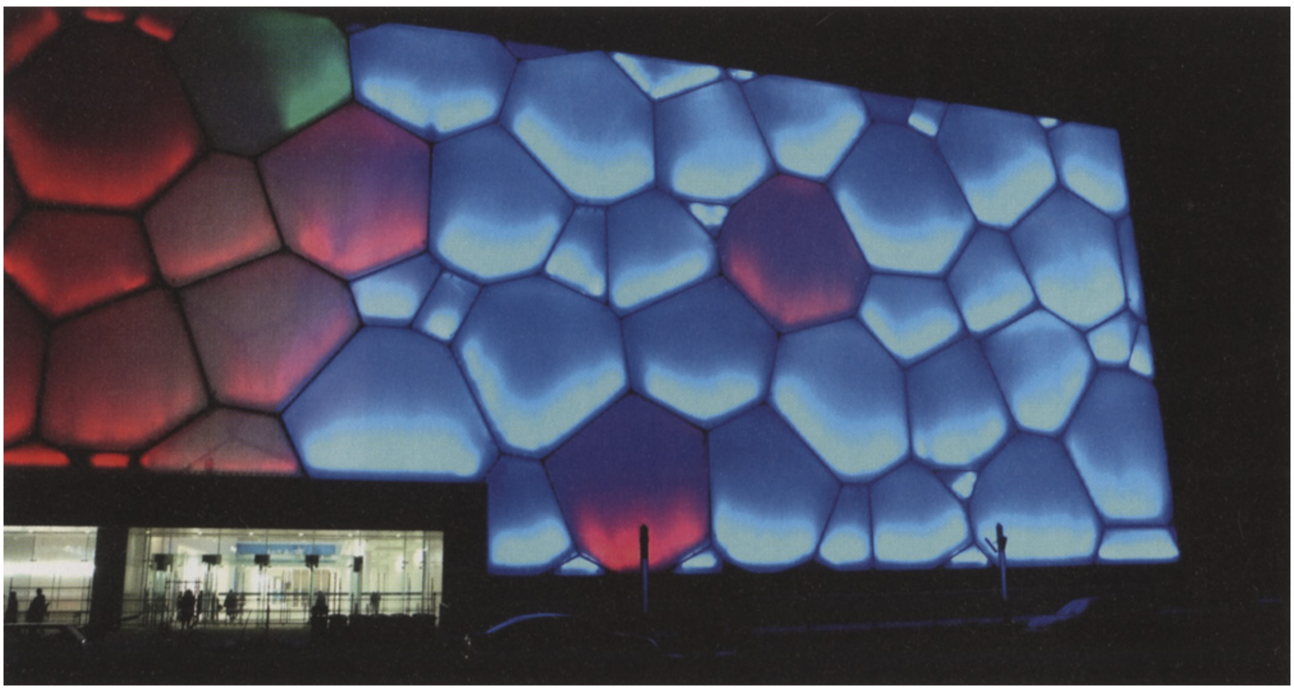


5

In order to assess the future for ETFE, it is worth examining the forces that shape architectural development: Reduction of prime and maintenance cost; improvement of long-term performance; better environmental performance; lower use of energy and recyclability are all major factors that contribute to the success of a technology. The use of ETFE satisfies all of these objectives and in many cases furthers them. The technology is highly economic, and long lasting and delivers high performance over many years whilst using a fraction of the energy of any alternative. At the end of a building's life, it can be recycled and reused. That being said, the development of what is in essence a very simple idea – the use of air to create a cladding system constructed from two or more transparent membranes – is in fact fiendishly complex and challenges many of the key architectural and structural concepts underlying normative approaches to the building envelope.

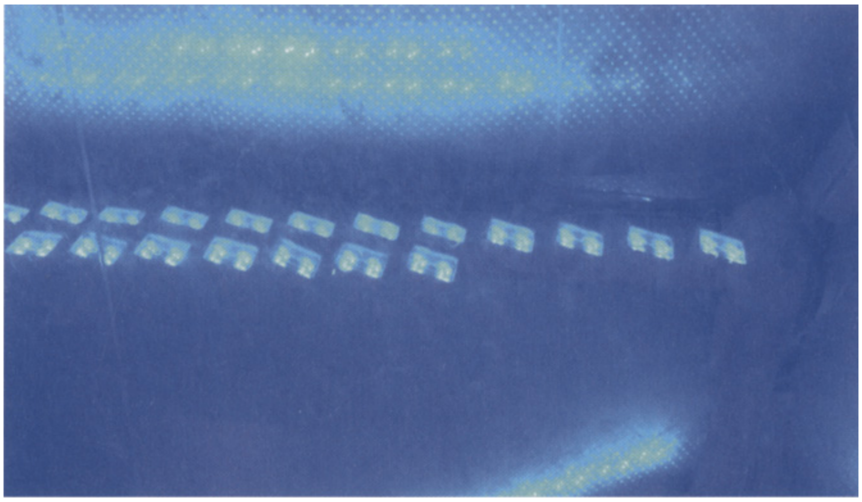
Conventional wisdom sees strength as a key attribute of building components, where the addition of more material makes a component stronger and safer. Against intuition, for ETFE, adding material results in failure. Hence, one must conceive of ETFE as a material that reacts through elasticity and plasticity to absorb, spread and dissipate loads rather than fight them. Further, it is a material that can shape morph to change its loadcarrying characteristics.

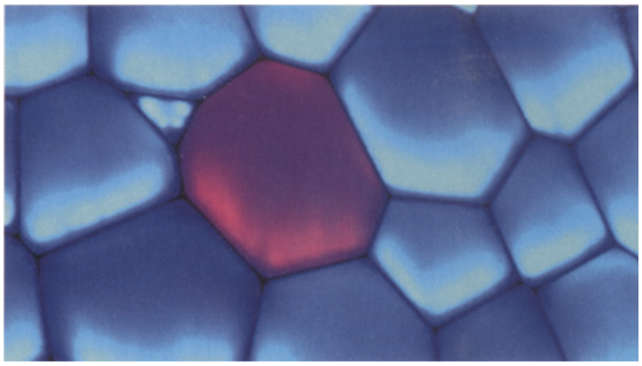
Conventional wisdom fights cladding movement and concentrates it at specific locations where special details need to be provided. ETFE allows the adoption of a detailing strategy of spreading movement over the whole building envelope rather than concentrating movement at junctions.

Conventional wisdom attempts to restrict deflection with much material being invested to prevent buildings from bending and flexing. ETFE cushions' containment of pressurized air has huge abilities to absorb and damp deflections, minimizing material usage and allowing completely different philosophies of engineering to develop.

Conventional approaches to fire safety view large volume spaces as high risk areas necessitating the use of sprinklers and mechanical equipment to extract and vent smoke. ETFE cushions react to fire by disappearing. Either through ETFE's ability to self vent or its ability to fail on demand, the inside becomes outside.

Most approaches analyze the envelope as a system to separate the interior from exterior space. ETFE cushions





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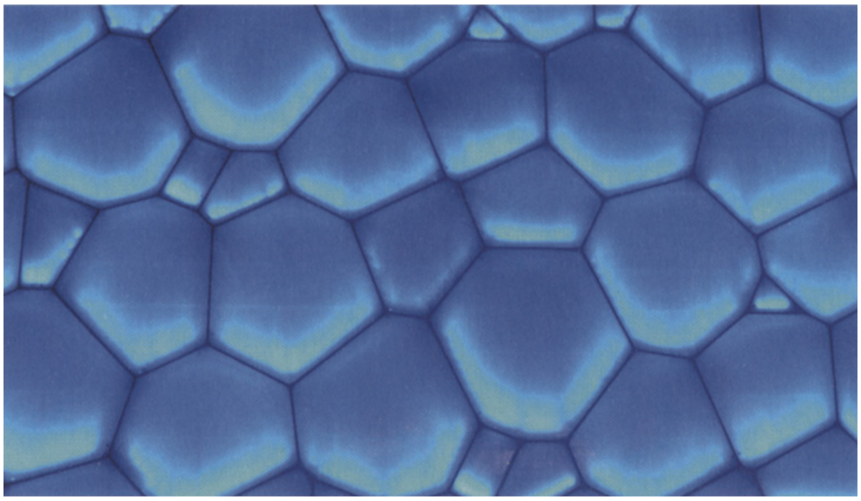

6 7

3–4__LEDs housed between the inner and outer cushions transform the building envelope into a dynamic communicative skin. / 5–8__In addition to working as a thermal duvet to support passive servicing strategies, the ETFE envelope of the Water Cube entertains. /

embrace the vagaries of climate and allow both the harvesting and manipulation of natural forces. They change their transmissivity and insulative qualities on demand to lower energy requirements and enhance the built environment.

Perhaps the question isn't so much whether ETFE cushion envelope will fade with passing architectural fashion but rather whether the technology is the ambassador of a group of building technologies that work with rather than against nature, and that harness natural forces to humanity's benefit rather than attempting to crush and conquer.

The invention and development of ETFE cushion envelopes has been paralleled by a technical revolution as far-reaching as the industrial revolution of the 17th and 18th centuries. As the digital age sweeps over us, instant information and communication are becoming embedded in our daily lives. Buildings are typically extremely conservative, and it is no accident that we have only noticed small inroads of the digital age into our built environment.

Over the last few years we have seen the rise of informative building envelopes that have been specifically designed to brand, to advertize or to communicate in the public domain. ETFE is at the forefront of this revolution. Ideas originating in the Air Pavillion at Magna Project and Heron Quays have been developed further in Basel Stadium, Allianz Arena and now the National Aquatics Center in Beijing where the whole façade is animated by LED lighting, changing and reacting on demand. The Vector Foiltec group has recently synthesized integrated LED lighting grids into inflated cushions, thus enabling for the first time the fusion of transparent enclosure with information technology to create huge graphic envelopes. The evolution of the communicative envelope is a very natural cultural expression of change in society at large. Coupled with the leaps and bounds we are making in optical transparency, this will ensure the growth and development of ETFE technology over the foreseeable future.

Project Credits

Mangrove Hall, Burgers' Zoo (p. 33–34)	
Arnhem, The Netherlands	
1982	
Client	Burgers' Zoo
Architect	ABT Adviesbureau voor Bouwtechniek
Contractor	Burgers' Zoo
ETFE contractor	Vector Foiltec

Tropical Hall, Burgers' Zoo (p. 35)	
Arnhem, The Netherlands	
1988	
Client	Burgers' Zoo
Architect	ABT Adviesbureau voor Bouwtechniek
Structural engineer	ABT Adviesbureau voor Bouwtechniek
Contractor	Burgers' Zoo
ETFE contractor	Vector Foiltec

Chelsea and Westminster Hospital (p. 72)	
London, United Kingdom	
1990	
Client	Chelsea and Westminster Hospital
Architect	Sheppard Robson
Structural engineer, building	Waterman Group
Structural engineer, atrium roof	Buro Happold
Services engineer	DSSR
Fire engineer	Crafer Associates
Quantity surveyor	Gleeds
Contractor	John Laing Construction
ETFE contractor	Vector Foiltec

Desert Hall, Burgers' Zoo (p. 34)	
Arnhem, The Netherlands	
1993	
Client	Burgers' Zoo
Architect	ABT Adviesbureau voor Bouwtechniek
Structural engineer	ABT Adviesbureau voor Bouwtechniek
Contractor	Burgers' Zoo
ETFE contractor	Vector Foiltec

Hampshire Tennis and Health Club (p. 51)	
Eastleigh, United Kingdom	
1995	
Client	The Hampshire Tennis and Health Club
Architect	Evan Borland Architects
Structural engineer	Buro Happold
Services engineer	Buro Happold
Contractor	Try Build Ltd.
ETFE contractor	Vector Foiltec

Air Pavilion, Magna Project (p. 52–55)	
Rotherham, South Yorkshire, United Kingdom	
2000	
Client	The MAGNA Trust
Architect	Wilkinson Eyre Architects
Structural engineer	Bingham Cotterell Mott MacDonald
Services engineer	Buro Happold
Fire engineer	FEDRA
Quantity surveyor	Deacon + Jones
Landscape architect	Hyland Edgar Driver
Exhibition design	Event Communications Ltd.
Structural engineer, Air Pavilion	AtelierOne
ETFE contractor	Vector Foiltec

Cyclebowl (p. 95–97)	
Hanover, Germany	
2000	
Client	Duales System Deutschland AG
Architect and general planning	Atelier Brückner
Structural engineer	Baustatik Relling
Services engineer, structure technology, climate concept and façade	Arup
Scenography	Atelier Brückner
Media	Jangled Nerves
Film	Mediamutant
Tornado	Ned Kahn, Sebastopol
Lighting	Luna Lichtarchitektur
Contractor	Nussli
ETFE contractor	Vector Foiltec

Festo Technology Center (p. 98)	
Esslingen, Germany	
2000	
Client	Festo AG
Architect	Jaschek und Partner
Lighting	Professor Axel Thallemer, Festo AG
Hardware/software	ag4 mediatecture
Contractor	Festo AG
ETFE contractor	Vector Foiltec

Living 2000 (p. 85)	
Hanover, Germany	
2000	
Client	Deutsche BauBeCon Holding
Architect	Willen Associates Architekten
Structural engineer	Lichti + Laig GmbH, ARCO – Planungsgesellschaft
Services engineer	Atelier Ten, EGU GmbH
Contractor	Deutsche BauBeCon Holding
ETFE contractor	Vector Foiltec

Eden Project (p. 66–69)	
Humid Tropics and Warm Temperate Biomes	
St. Austell, Cornwall, United Kingdom	
2001	
Client	The Eden Project Ltd.
Architect	Grimshaw
Structural engineer	Anthony Hunt Associates
Services engineer	Arup
Quantity surveyor	Davis Langdon + Everest
Contractor	Sir Robert McAlpine Ltd.; Alfred McAlpine Ltd. Joint Venture
Project manager	Davis Langdon Management

Project supervisor	Land Architects Ltd.
Planning supervisor	Aspen Burrow Crocker
Landscape architect	Land Use Consultants
Fire engineer	Arup Fire
Façade consultant	Arup Façades
Access consultant	Purcell Miller Tritton
Steelwork a. cladding contractor	Mero UK plc
ETFE contractor	Vector Foiltec

National Space Centre (p. 63)
Leicester, United Kingdom
2001

Client	National Space Centre Property Co. Ltd.
Architect	Grimshaw
Structural engineer	Arup
Services engineer	Arup
Fire engineer	Locke Carey Associates
Acoustics	Sandy Brown Associates
Façade consultant	Montresor Partnership
Quantity surveyor	Capita Property Services
Landscape architect	Land Use Consultants
Contractor	Sir Robert McAlpine Ltd.
Project manager	Gardiner Theobald Management
Cladding contractor	Skyspan/Broderick

DBU Conference and Exhibition Building (p. 49)
Osnabrück, Germany
2002

Client	German Federal Environmental Foundation (DBU)
Architect	Herzog + Partner
Structural engineer	Barthel und Maus
Membrane engineer	Tensys
Mechanical services	NEK Ingenieur Gruppe
Energy technology consultant	ZAE Bayern e.V.
Acoustics	Müller-BBM
Daylight simulation and measurement	Lehrstuhl für Gebäudetechnologie, Munich Technical University
Landscape architect	Latz + Partner
Site supervision	Reinders + Partner
ETFE contractor	Hightex

Her Majesty's Treasury (p. 75)
London, United Kingdom
2002

Client	Her Majesty's Treasury; Exchequer Partnership; Stanhope plc; Bovis Lend Lease; Chestertons
Architect	Foster and Partners
Structural engineer	Waterman Partnership
Services engineer	JBB
Environmental engineer	BDSP Partnership
Logistics	Arup; Jolyon Drury Consultancy
Space planning	DEGW
Fire engineer	Warrington Fire Research
Cost consultant	Hanscomb Partnership; Mott Green Wall
Acoustics	Hann Tucker

Landscape architect	Gustafson Porter
Lighting	Spiers and Major
Historic building advisor	Fielden and Mawson
Access consultant	David Bonnet
Color consultant	Per Arnoldi
Main contractor	Bovis Lendlease
ETFE contractor	Vector Foiltec

Kapuzinercarrée (p. 74)
Aachen, Germany
2002

Architect	Ingenhoven Overdiek + Partner
Structural engineer	KKK Ingenieurgesellschaft mbH
Special structural analysis	Werner Sobek Ingenieure
Building services	Intecplan
Façade consultant	DS-Plan
Building physics	DS-Plan
Lighting	Tropp Lighting Design
Surveying	Vermessungsbüro Kroll
Fire engineer	BPK Brandschutz-Planung Klingsch
Landscape architect	Ingenhoven Overdiek + Partner
ETFE contractor	Vector Foiltec

Los Angeles County Museum of Art (p. 64–65)
Los Angeles, California, USA
2002, competition scheme

Architect	OMA
Structural engineer	Arup
Services engineer	Arup
Quantity surveyor	Donnellan Lynch + Associates

Piccadilly Station (p. 50)
Manchester, United Kingdom
2002

Client	Railtrack
Architect	Building Design Partnership
Structural engineer	URS
Services engineer	Building Design Partnership
Quantity surveyor	Turner Townsend
Contractor	Laing O'Rourke
ETFE contractor	Vector Foiltec

Heron Quays Station, Docklands Light Railway (p. 127)
London, United Kingdom
2003

Client	DLR/Canary Wharf plc Joint Venture
Architect	Alsop Architects
Rail and structural engineer	WS Atkins
Services engineer	WS Atkins
Fire engineer	Arup Fire
Quantity surveyor	AYH Plc
Lighting	Light Matters
Contractor	Canary Wharf Contractors
ETFE contractor	Vector Foiltec

Meiderich Theater (p. 60–62)
Duisburg, Germany
2003

Client	Landschaftspark Duisburg-Nord GmbH; Kultur Ruhr GmbH
Architect	planinghaus architekten
Conservation consultant	Büro für Industriearchäologie
Structural engineer, travelling roof	Schlaich Bergermann und Partner
Structural engineer, existing structures	Röber + Partner
Services engineer	Cosanne Ingenieure
Steel contractor, roof mechanism	Waagner-Biro Bavaria Stage Systems GmbH
ETFE contractor	Vector Foiltec

National Gallery (p. 76)
London, United Kingdom
2003

Client	National Gallery
Architect	Purcell Miller Triton
Contractor	Mansell Construction Services Ltd.
ETFE contractor	Vector Foiltec

Pool Elypso (p. 41)
Deggendorf, Germany
2003

Architect	PFG Planungsgesellschaft; Gollwitzer Architekten
Stuctural engineer, roof	Ingenieurbüro Häusler
Structural engineer, membrane	Plantec Planungs GmbH
Contractor	Stadtwerke Deggendorf
ETFE contractor	Vector Foiltec

Art Center, College of Design, South Campus (p. 104–111)
Pasadena, California, USA
2004

Client	Art Center College of Design
Architect	Daly Genik Architects
Structural engineer, courtyard	Gilsanz Murray Steficek
Structural engineer, building reinforcing	Englekirk & Sabol
Structural engineer, skylights	Arup
Services engineer	Ideas for the Built Environment
Civil engineer	KPFF
Landscape	Nancy Goslee Power & Associates
Code consulting	Schirmer Engineering Corporation
Sustainability	Loisos + Ubbelohde
Graphic design	Bruce Mau Design
Signage	Hunt Design Associates
Acoustics	McKay Conant Brook
Air ventilation	Shen Milson Wilke/Paoletti
Contractor	Turner Special Projects
Construction management	Lowe Enterprises
ETFE contractor	Vector Foiltec

DomAquarée (p. 118–121)
Berlin, Germany
2004

Client	Deutsche Immobilien Fonds AG
Architect	nps tchoban voss architekten
Landscape architect	Lützow 7
Project control	Kappes Scholtz Ingenieur Planungsgesellschaft mbH
Technical project coordination	Generalplaner Technik DomAquarée
Structural engineer	Leonhardt, Andrä und Partner Beratende Ingenieure GmbH
Mechanical services	Kuehn Bauer Partner
Construction supervision	Gesellschaft fur Städtebau und Projektentwicklung Berlin mbH
Quality management	Ingenieurgesellschaft Schlapka AG Planungsbüro Rohling AG Architekten und Ingenieure
Lighting	Kardorff Ingenieure
Elevators	Hundt + Partner
Façade consultant	Priedemann Fassadenberatung
Acoustics	Büro Bernhard Marx
Energy flow and simulation	Institut für angewandte Energie- und Strömungssimulation
Fire engineer	HHP Berlin
Aquarium	International Concept Management Reynolds Polymer Technology
ETFE contractor	Vector Foiltec

Jean-Paul Gaultier Headquarters (p. 77)
Paris, France
2004

Client	Groupe Jean-Paul Gaultier SA
Architect	Alain Moatti + Henri Rivière
Structural engineer	RFR
Services engineer	ALTO
ETFE contractor	Vector Foiltec

Kingsdale School (p. 99–103)
Dulwich, London, United Kingdom
2004

Client	Southwark Education, London Borough of Southwark
Architect	de Rijke Marsh Morgan Architects (dRMM)
Structural engineer	Michael Hadi Associates
Services engineer	Fulcrum Consulting
Quantity surveyor	Appleyard & Trew
Project manager	Southwark Building Design Services
Acoustics	Fleming & Barron
Light, air and sound 'cannon'	Atelier von Lieshout
Contractor	Galliford Try Construction (South)
Structural steelwork	SH Structures
ETFE contractor	Vector Foiltec

Oval at Baseler Platz (p. 56–57)
Frankfurt, Germany
2004

Client	BGA – Allgemeine Immobilien-verwaltungs- und Entwicklungs-gesellschaft mbH
Architect	AS&P – Albert Speer & Partner
Structural engineer	B+G Ingenieure Bollinger und Grohmann
Services engineer	HL Technik
General contractor	Joint Venture Arge Oval am Baseler Platz, Wayss & Freytag Schlüsselfertigbau AG; BauBeCon Hochbau GmbH
ETFE contractor	Vector Foiltec

Tanaka Business School, Imperial College (p. 116–117)
London, United Kingdom
2004

Client	Imperial College
Architect	Foster and Partners
Structural engineer	Buro Happold
Project manager	Gardiner and Theobald Management Services
Lighting	Buro Happold
Services engineer	Buro Happold
Planning supervisor	Jenkins and Potter
Quantity surveyor	DL+E
Fire engineer	Warrington Fire Research
Acoustics	Sandy Brown Associates
Façade consultant	Hyder Consulting
Pedestrian analysis	Halcrow Group
ETFE contractor	Vector Foiltec

Allianz Arena (p. 128–131)
Frottmaning, Munich, Germany
2005

Client	München Stadion GmbH
Architect	Herzog & de Meuron
Sports architecture	ArupSport
Bowl and roof structural design competition scheme	ArupSport
Bowl structural design, construction	Arup GmbH
Roof structural design, construction	Sailer Stephan und Partner
Façade structural design	R + R Fuchs
Pneumatic skin calculation	Engineering + Design
Services engineer	TGA-Consulting
Project management and quantity surveyor	HVB Immobilien
Checking engineer	Dr. D. Linse
General contractor	Alpine Bau Deutschland GmbH
Steel contractor	Max Bogl Stahl- und Anlagenbau GmbH
Lighting design and contractor	Siteco
ETFE cushion manufacturer	KfM GmbH
ETFE contractor	Covertex

Frøsilo Flats (p. 58–59)
Copenhagen, Denmark
2005

Client	Gemini Residence A/S
Architect	MVRDV in cooperation with Jenson + Jorgensen + Wohlfeldt
Structural engineer	ABT Adviesbureau voor Bouwtechniek; Ramboll
Services engineer	NCC Construction A/S, Teknik
Contractor	NCC Construction Danmark A/S
Landscape architect	Bisgaard Landskabsarkitekter
ETFE contractor	Vector Foiltec

The Mall (p. 122)
Athens, Greece
2005

Architect	Ergotex
Contractor	Lamda Development
ETFE contractor	Vector Foiltec

Clarke Quay (p. 81–83)
Singapore
2006

Client	Capitaland Commercial Ltd.
Architect	Alsop Architects
Local architect and structural engineer	RSP Architects Planners + Engineers
Specialist engineering	Tensys
Concept engineer	AtelierOne
Environmental engineer	Arup
Services engineer	Squire Mechanical
Contractor	Kajima
Façade consultant	Arup Façades
ETFE contractor	B+O Hightex

Saint Jacob Stadium (p. 132–135)
Basel, Switzerland
2006

Client	Genossenschaft Stadion St. Jakob-Park
Architect	Herzog & de Meuron
Structural engineer	WGG Schnetzer Puskas Ingenieure AG Rothpletz, Lienhard + Cie
Contractor	Batigroup AG
ETFE contractor	Vector Foiltec

Southern Cross Station (p. 78–80)
Melbourne, Australia
2006

Client	Leighton Contractors Pty Ltd.
Architect	Grimshaw Jackson JV
Joint venture architect	Jackson Architecture
Main contractor	Leighton Contractors Pty Ltd.
Structural engineer	Winward Structures
Services engineer	Lincolne Scott Australia P/L

Environmental engineer	AEC (Advanced Environmental Concepts)
Rail infrastructure	Maunsell Australia
Signalling	GHD
Pedestrian analysis	Scott Wilson Irwin Johnson Pty Ltd.
Disability management	Blythe Saunderson
Security	Honeywell
Acoustics	Marshall Day
Roof shop detailing	Precision Design
ETFE contractor	Vector Foiltec

Discovery Bay School (p. 84)
Hong Kong, China
2007

Client	English Schools Foundation
Project management	Ove Arup & Partners Hong Kong
Architect	Integrated Design Associates
Structural, civil and geotechnical engineer	Maunsell Structural Consultants
Building services engineer	J. Roger Preston
Quantity surveyor	Widnell
Environmental and venue consultant	Ove Arup & Partners Hong Kong
Landscape consultant	Austin and Rayner Design
ETFE contractor	Wise Dragon Engineering

John Wheatley College (p. 112–113)
Glasgow, United Kingdom
2007

Client	John Wheatley College, Shettleston Campus
Client consultant	Capita Symonds Ltd.
Architect	Ahrends Burton & Koralek
Structural engineer	Buro Happold
Services engineer	Buro Happold
Quantity surveyor	Doig + Smith
Catering	Sterling Foodservice Design
Landscape architect	Landesign
Contractor	HBG Construction Ltd.
ETFE contractor	Vector Foiltec

Transport Interchange, Terminal 5, Heathrow Airport (p. 123–125)
London, United Kingdom
2008

Client	BAA
Architect	Richard Rogers Partnership
Masterplan and lead architect	Richard Rogers Partnership
Co-architects	Pascal + Watson (production) Chapman Taylor (retail) HOK (rail systems) YRM (BAA liaison)
Civil engineer	Mott McDonald
Structural engineer	Arup
Services engineer	DSSR; Arup
Quantity surveyor	Turner + Townsend; E.C. Harris
Construction management	BAA
Principal contractors	Laing O'Rourke; Mace; Balfour Beaty; AMEC

Transport Interchange roof

Lead architect	HOK
Structural engineer	Arup
Main contractor	Balfour Beatty Construction Ltd.
Structural steelwork	Rowens
Services contractor	Balfour Kilpatrick
Elevators	Schindler
Glass and fittings – design and installation	Lindner Schmidlin (LSF)
Glass and fittings – manufacture and supply	Schmidlin TSK
ETFE contractor	Vector Foiltec

Khan Shatyry Entertainment Center (p. 138–139)
Astana, Kazakhstan
2008

Client	Sembol Construction
Architect	Foster and Partners
Contractor	Sembol Construction
Structural engineer	Buro Happold
Services engineer	Buro Happold
Local architect	Linea, Gultekin and UMO
Local structural engineer	Ergun Tercanlý
Local services engineer	Vemeks
Retail consultant	Avi Alkas
Landscape consultant	Dr. Metin Baþa
Fire consultant	Dr. Abdurahman Kiliç (Istanbul Technical University) Dr. Kazim Beceren (Istanbul Technical University)
Cable net design	Teschner
Cable net contractor	Montageservice
ETFE contractor	Vector Foiltec

National Aquatics Center (p. 86–93)
Beijing, China
2008

Client	Beijing State-Owned Assets Management Co. Ltd.
Architect	PTW (Australia) + CSCEC Shenzhen Design Institute (CSCEC + Design)
Lead consultant	CSCEC (China State Construction Engineering Corporation)
Structural engineer	Arup + CSCEC Shenzhen Design Institute (CSCEC + Design)
Services engineer	Arup + CSCEC Shenzhen Design Institute (CSCEC + Design)
Fire engineer	Arup + CSCEC Shenzhen Design Institute (CSCEC + Design)
Project manager	Three Gorges Corporation
Specialist consultant	Shenzhen Institute
Main contractor	CSCEC (China State Construction Engineering Corporation)
ETFE contractor	Vector Foiltec

The Authors

Parkview Green Plaza (p. 140–143)
Beijing, China
2008

Client	Beijing Chyau Fwu Development Co.
Architect	Integrated Design Associates
Project management	Jandun Construction Company
Local architect	Beijing Institute of Architectural Design + Research
Building physics	Ove Arup & Partners Hong Kong
Structural, services and fire engineer	Ove Arup & Partners Hong Kong
Quantity surveyor	Levett and Bailey Quantity Surveyors
Façade consultant	Ove Arup & Partners Hong Kong
Landscape architect	Integrated Design Associates and Beijing Institute of Architectural Design + Research
Lighting	Fisher Marantz Stone
ETFE contractor	Vector Foiltec

Earthpark (p. 144–145)
Pella, Iowa, USA
2010

Client	Earthpark
Architect	Grimshaw
Associate architect	RDG Planning + Design
Structural engineer	Thornton-Tomasetti Engineers
Services engineer	Syska Hennessy Group
Exhibit design	Lyons Zaremba
Contractor	Weitz Turner

Annette LeCuyer

Annette LeCuyer is an architect, critic and educator. She studied at the Architectural Association, worked in practice in London and has written extensively for architectural publications in Europe and North America. She is the author of several books on contemporary architecture and building technology including *Steel and Beyond – New Strategies for Metals in Architecture* and is a regular contributor to *The Architectural Review*. She is a professor of architecture at the University at Buffalo, The State University of New York.

Stefan Lehnert

Dr. Stefan Lehnert studied mechanical engineering at Hanover University of Technology. An additional degree in business administration and a Ph.D. thesis on strategic management processes at Braunschweig University of Technology laid the groundworks for establishing the Vector Foiltec Group in 1982. Since starting the development of ETFE systems for architectural applications he has been a director and joint partner of Vector Foiltec in Bremen. His expertise in mechanical engineering helped in the development of ETFE welding equipment and his life-long experience in developing high level ocean racing sails was instrumental to developing technical solutions for ETFE foil systems.

Ian Liddell

Ian Liddell is a structural engineer. He studied mechanical sciences at Cambridge University followed by a diploma in concrete structures at Imperial College, London. He was one of the founding partners of Buro Happold and the designer of London's Millennium Dome as well as project engineer on the Sydney Opera House, playing a significant role in the form finding of the iconic roofs. Liddell continues to work as a consultant for Buro Happold. He received the Gold Medal of the Institution of Structural Engineers in 1999 and is a Royal Academy Visiting Professor of Engineering Design at Cambridge University School of Engineering.

Ben Morris

Ben Morris is an architect, designer, and maker of things. He studied at Hornsey College of Art and various schools of architecture. Morris is a director and joint partner of Vector Foiltec in London and has been responsible for many of the key designs and technical innovations in ETFE. He is a keen sailor and many key structural principles have first been tested at sea.

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